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THE DIRECTIONAL ANALYSIS  
OF OCEAN WAVES:  
AN INTRODUCTORY DISCUSSION  
(SECOND EDITION)

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## ABSTRACT

An introductory discussion of the mathematics behind the directional analysis of ocean waves is presented. There is sufficient detail for a reader interested in applying the methods; further, the report can serve as an entry into the theory. The presentation is basically tutorial but does require a reasonably advanced mathematical background. Results of a program for the measurement of directional ocean wave bottom pressure spectra are included as an appendix. This second edition makes corrections to the first and adds some details of an iterative directional analysis method.

## ADMINISTRATIVE INFORMATION

This report was prepared to document the mathematical methods used in connection with work done in support of Task SWOC SR 004 03 01, Task 0582, and applied on Task ZR 000 01 01, Work Unit 0401-40.

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## 1. INTRODUCTION

The report presents an introductory discussion of the mathematics pertaining to the directional analysis of ocean waves. The presentation is tutorial in form but does require a reasonably complete mathematical background; a background equivalent to that required in reading Kinsman's textbook *Wind Waves* (1965).

The level of the presentation is moderate at the beginning. The level picks up rapidly toward the middle but there should be sufficient detail and redundancy in the mathematics to allow the reader to follow the development without having to rediscover too many omitted steps. It is in this sense that the report is tutorial. In some places the mathematical development is intuitive rather than rigorous. This is deliberate in order to provide insight and understanding. In most such cases, references to rigorous reports are given.

The development is reasonably detailed so that the interested reader may apply the methods presented and use the report as an entry point into the rigorous theory of the directional analysis of ocean waves. In this respect, if the report serves as a bridge across the gap between a handbook and a rigorous and sparse theory on the subject then the objective of the report will have been fulfilled.

The report first presents an intuitive development of a sea surface model that assumes the sea surface to be a two-dimensional random process definable in terms of a directional power spectrum. A discussion of the space and time covariance function and its relationship to the directional power spectrum follows. Both one- and two-sided power spectra are discussed; however, the main development is in terms of the two-sided spectrum. Next, the relationship between the power and cross power spectrum for two fixed locations and the sea surface directional spectrum is developed. Explicit relationships for the special cases of an isotropic sea and a single wave of a given direction and frequency are then obtained. The related topic of the directional resolving power of an array of wave transducers is then presented.

Using the preliminary developments as a basis, several methods for the directional analysis of ocean waves based on the information obtainable from an array of wave transducers are presented. The methods

are basically a direction finder technique, a least square single-wave train fit, and a Fourier-Bessel expansion fit. In conclusion, a generalized Fourier expansion method is suggested. Extensive results of the application of the least square single-wave train fit are presented in Appendix A. Appendix B is a FORTRAN II listing of a program for this analysis.

## 2. WAVE MODELS

In its simplest form an ocean wave can be thought of as a single frequency, sinusoidal, infinitely long crested wave of length  $\lambda$ , moving in time over the ocean surface from a given direction  $\theta$ . Such a wave is illustrated in Figure 1.

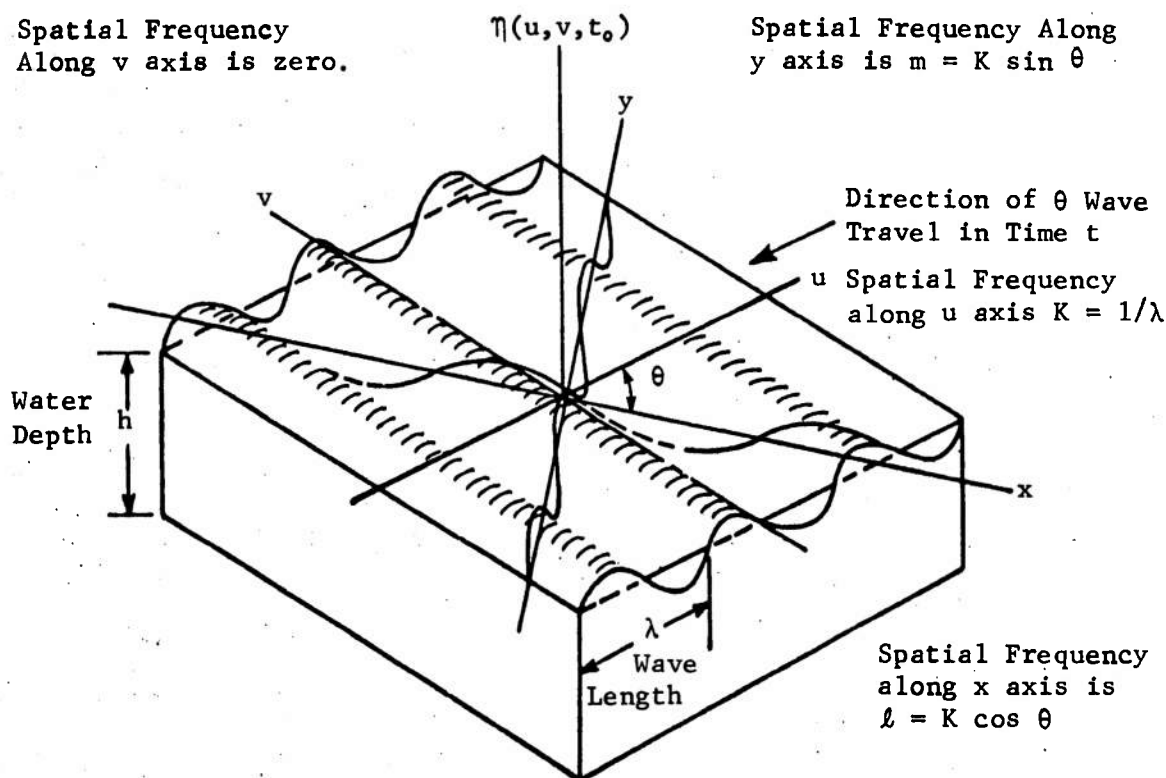


FIGURE 1. SIMPLE OCEAN WAVE

Assume that the wave is frozen in time over the surface (the x,y spacial plane). The coordinates (u,v) are a  $\theta$  degree rotation of the (x,y) coordinates. The positive u axis lies along the direction from which the wave is traveling. The wave surface  $\eta(u,v)$ , shown frozen in time in Figure 1 can be described mathematically by

$$\eta(u,v) = \cos(2\pi Ku + 2\pi\phi) \quad (2.1)$$

where  $K = 1/\lambda$  is the wave number of spacial frequency in cycles per unit length along the u axis, and  $2\pi\phi$  is a spacial phase shift.

To make the wave move in time across the spacial plane with a time frequency  $f = 1/p$ , where p is the wave period, it is necessary to add a time part to the argument of the cosine function in the model above. The time part is a phase shift dependent only upon time. As time passes, the time part changes causing the cosine wave to move across the (u,v) plane, in this case the ocean surface. Adding the time part we get (where  $2\pi\psi$  is a fixed time phase shift)

$$\eta(u,v,t) = \cos(2\pi Ku + 2\pi\phi + 2\pi ft + 2\pi\psi).$$

If we combine the effect of the  $\phi$  and  $\psi$  phase shifts as  $\alpha = \phi + \psi$ , we get

$$\eta(u,v,t) = \cos(2\pi(Ku + ft + \alpha)) \quad (2.2)$$

as a simple model of a sinusoidal wave moving in time over the ocean surface.

Since the coordinates (u,v) are a rotation of the coordinates (x,y) through an angle of  $\theta$  degrees, we know

$$\begin{aligned} u &= x \cos \theta + y \sin \theta \\ v &= -x \sin \theta + y \cos \theta. \end{aligned}$$

Using the above relations, and letting  $\ell = k \cos \theta$  and  $m = K \sin \theta$  be the spacial frequencies along the x and y axes, respectively, we have

$$\eta(x,y,t) = A \cos(2\pi(\ell x + my + ft + \alpha)) \quad (2.3)$$

as a model for a wave of height 2A moving from a direction

$$\theta = \arctan (m/\ell)$$

with a phase shift of  $2\pi\alpha$ . A wave crest of such a wave system is infinite in length. A crest occurs at a set of points (x,y,t) which satisfy the relation

$$\ell x + my + ft = \text{a constant} = (n - \alpha)$$

where  $n = 0, -1, +1, -2, +2, \dots$ . Each value of the index  $n$  relates to a particular crest. The intersections of the crests with the  $x$  and  $y$  axes move along the respective axes with time velocities  $V_x = -f/\ell$  and  $V_y = -f/m$ . This follows from the differential expressions

$$D_c(x) = D_t \left[ \frac{n-\alpha}{\ell} - \frac{m}{\ell} y - \frac{ft}{\ell} \right] = -\frac{f}{\ell} \quad (2.4)$$

$$D_c(y) = D_t \left[ \frac{n-\alpha}{m} - \frac{\ell}{m} x - \frac{ft}{m} \right] = -\frac{f}{m} \quad (2.5)$$

obtained from the wave crest relationship given above.

From Euler's equation we know that  $\cos \gamma = (\text{Exp}(i\gamma) + \text{Exp}(-i\gamma))/2$ . If we consider  $\gamma$  as  $2\pi(\ell x + my + ft + \alpha)$  we can write

$$\eta(x, y, t) = 1/2A \text{Exp}(i2\pi(\ell x + my + ft + \alpha)) + 1/2A \text{Exp}(i2\pi(-\ell x - my - ft - \alpha)) \quad (2.6)$$

where  $-\infty < \ell < +\infty$ ,  $-\infty < m < +\infty$  and  $-\infty < f < +\infty$ .

In the above we have introduced the notion of negative time frequencies. This makes it possible to express an elementary wave in the mathematically convenient form

$$\eta(x, y, t) = a \text{Exp}(i2\pi(\ell x + my + ft + \alpha)) \quad (2.7)$$

where  $a = 1/2A$ . In the real world a complex wave of this type implies the existence of another wave  $\eta^*(x, y, t)$  which is the complex conjugate of  $\eta(x, y, t)$  above. This complex conjugate is given by

$$\begin{aligned} \eta^*(x, y, t) &= a \text{Exp}(-i2\pi(\ell x + my + ft + \alpha)) \\ &= a \text{Exp}(i2\pi[(-\ell)x + (-m)y + (-f)t + (-\alpha)]). \end{aligned} \quad (2.8)$$

The fact that negative frequencies are considered is explicit in the above relation.

A property of the above model, which will be used later in connection with the directional analysis of waves from measurements obtained from an array of detectors, is expressed by the equation for the phase difference of two measurements made at two different points in space and time. Assume we know the value of  $\eta(x, y, t)$  at the three-dimensional coordinates  $(x_0, y_0, t_0)$  and  $(x_0+X, y_0+Y, t_0+T)$ , where  $X$ ,  $Y$ , and  $T$  are constants. The phases at the two points are given by



$$\phi(x_0, y_0, t_0) = \ell x_0 + m y_0 + f t_0 + \alpha, \quad (2.9)$$

$$\phi(x_0 + X, y_0 + Y, t_0 + T) = \ell(x_0 + X) + m(y_0 + Y) + f(t_0 + T) + \alpha \quad (2.10)$$

This gives a phase difference of

$$\Delta\phi = (\ell X + mY + fT). \quad (2.11)$$

To obtain a more complicated wave system consisting of many waves of various frequencies and directions, we can linearly superimpose (add up) many waves of the form given above. If we do this, we can write

$$\eta(x, y, t) = \sum_{n=1}^N Q_n \exp(i 2\pi(\ell_n x + m_n y + f_n t + \alpha_n)). \quad (2.12)$$

For this wave system to be real, the terms must occur in complex conjugate pairs as indicated above.

For completeness, consider a model for an infinite but countable number of distinct (discrete) waves and write

$$\eta(x, y, t) = \sum_{n=1}^{\infty} a_n \exp(i 2\pi(\ell_n x + m_n y + f_n t + \alpha_n)). \quad (2.13)$$

Again the terms must occur in complex conjugate pairs for the wave system to be real. This will be assumed to be the case in future discussions.

A model for a wave system in the case where energy exists for continuous intervals of frequency and direction should be considered. In particular, consider the general case of continuous direction from 0 to  $2\pi$  radians and continuous frequency in the interval  $(-f_n, +f_n)$ , or even the interval  $(-\infty, \infty)$ . In theory the above model does not hold for the continuous case. The power spectrum for the infinite but countable case would be a set of Dirac delta functions of amplitude  $a_n^2$  standing on the points  $(\ell_n, m_n, f_n)$  of a three-dimensional frequency space. The continuous case produces a power spectrum,  $S_0(\ell, m, f)$ , which is everywhere nonnegative and in general continuous over the region of three-dimensional frequency space where power is assumed to exist. A reasonable model for  $\eta(x, y, t)$  in the continuous case must be determined. Consider a single wave element

$$a_n \exp(i 2\pi(\ell_n x + m_n y + f_n t + \alpha_n)). \quad (2.14)$$

The energy or mean square in this element is  $a_n^2$ . Assume the element is a part of a continuum of elements for  $-\infty < \underline{f} < +\infty$  and  $0 \leq \theta < 2\pi$ . In this case  $a_n^2$  must be an infinitesimal energy associated with the frequency differential,  $df$ , and space frequency differentials,  $d\ell$ , and  $dm$ , which are related to the direction  $\theta$  of the wave element as before. Let the power spectrum,  $S(\ell, m, f)$ , be defined with units of amplitude squared and divided by unit spacial frequency,  $\ell$ , unit spacial frequency,  $m$ , and unit time frequency,  $f$ . The power spectrum is then a spectral density value at  $(\ell, m, f)$ . In this case we must have the infinitesimal energy,  $a_n^2$ , defined by

$$a_n^2 = S(\ell, m, f) d\ell dm df \quad (2.15)$$

The real valued, nonnegative function  $S(\ell, m, f)$  is a power (energy density) spectrum of the standard type in three-dimensional frequency space  $(\ell, m, f)$ . Intuitively, we can write an infinitesimal wave element as

$$\left[ \exp(i 2\pi (\ell_n x + m_n y + f_n t + \alpha_n)) \right] \sqrt{S(\ell_n, m_n, f_n) d\ell dm df}, \quad (2.16)$$

where the positive square root is assumed. To arrive at a model of  $\eta(x, y, t)$  for the continuous case, we need only form a triple "sum" of the infinitesimals or, to be precise, the triple integral  $\eta(x, y, t) =$

$$\iiint_{-\infty}^{\infty} \exp(i 2\pi (\ell x + m y + f t + \alpha(\ell, m, f))) \sqrt{S(\ell, m, f) d\ell dm df} \quad (2.17)$$

For different sets of values of the phase relation  $\alpha(\ell, m, f)$ , the wave system,  $\eta(x, y, t)$ , has a different shape, even when  $S(\ell, m, f)$  is fixed. In fact there is a wide range of possible shapes of  $\eta(x, y, t)$  for a given  $S(\ell, m, f)$ . The above development is more intuitive than mathematically rigorous. It has been shown by Pierson (1955 - pp. 126-129) that if  $2\pi\alpha(\ell, m, f)$  is a random function such that for fixed  $(\ell, m, f)$  phase values of the form  $2\pi\alpha \text{ MOD } 2\pi$  between 0 and  $2\pi$ , are equally probable and all phase values are independent, then Equation (2.17) represents an ensemble (collection of all probable)  $\eta(x, y, t)$  for a given  $S(\ell, m, f)$ . The random process represented by the ensemble is then a stationary Gaussian process indexed by the three dimensions  $(x, y, t)$ . Detail discussions of the above can be found in St. Dennis and Pierson (1953 - pp. 289-386) and Kinsman (1965 - pp. 368-386). The fact that a particular sea-way can be considered as a realization of a stationary three-dimensional Gaussian process has been verified. Refer to Pierson and Marks (1952).

The model in Equation (2.17) as a stationary random process will be assumed in following discussion.

### 3. A DIRECTIONAL WAVE SPECTRUM

The power spectrum  $S(\ell, m, f)$  is the directional wave spectrum of  $\eta(x, y, t)$ . If  $\eta(x, y, t)$  is to be real, every infinitesimal of the form given in the continuous case above presumes the existence of its complex conjugate. Let us consider the one-sided power spectral density,  $S'(\ell_0, m_0, f_0)$ , of a single real wave where  $0 \leq f_0 < \infty$ . For such a real wave element of length  $\lambda_0$ , from a direction  $\theta_0$ ,  $0 \leq \theta_0 < 2\pi$ , the value  $S'(\ell_0, m_0, f_0) = S(\ell_0, m_0, f_0) + S(-\ell_0, -m_0, -f_0)$ , where  $\ell_0 = K_0 \cos \theta_0$ ,  $m_0 = K_0 \sin \theta_0$ , and  $K_0 = 1/\lambda_0$ . If the above real wave came from a direction  $(2\pi - \theta)$ , the power density would be  $S'(\ell_0, -m_0, f_0) = S(\ell_0, -m_0, f_0) + S(-\ell_0, m_0, -f_0)$ .

Figure 2 illustrates a real wave of length  $\lambda_0$ , from a direction  $\theta_0$ , in two-dimensional spacial frequency (wave number) space.

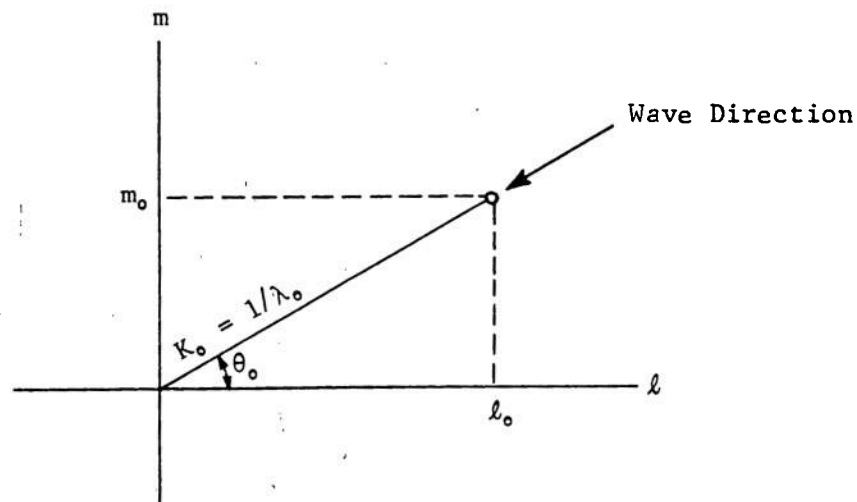


FIGURE 2. REAL WAVE IN WAVE NUMBER SPACE

If the wave number relation

$$K = 2\pi f^2 / g \tanh(2\pi K h) \quad (3.1)$$

holds, refer to Kinsman (1965 - p. 157) and Munk et al (1963 - p. 527), where  $h$  = water depth,  $g$  = acceleration of gravity, and  $K$  = wave number  $= 1/\lambda$ ,  $\lambda$  being the wave length; then a relationship between  $f$  and  $(\ell, m)$  is implied that requires a wave frequency  $f_0$  to have a unique wave number  $k_0$ . From this we have the general one-sided spectral form for waves where  $f = f_0$  of

$$S'(\ell, m, f_0) = \begin{cases} \text{zero where } \ell^2 + m^2 \neq K_0^2 \\ \text{a power density } \geq 0 \text{ for } \ell^2 + m^2 = K_0^2. \end{cases}$$

$S'(\ell, m, f_0)$  thus defines power density at  $f = f_0$  for wave energy over  $0 \leq \theta < 2\pi$ . Figure 3 illustrates this case in wave number space.

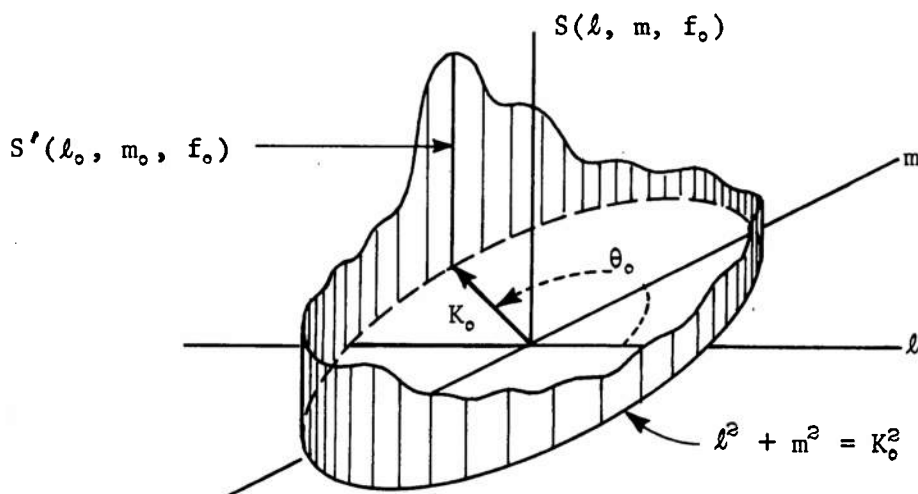


FIGURE 3. DIRECTIONAL WAVE SPECTRUM AT A FIXED FREQUENCY,  $f_0$

We want to estimate the shape of  $S'(\ell, m, f_0)$  above the circle  $\ell^2 + m^2 = K_0^2$  in a directional wave train analysis. Remember, the  $S'(\ell, m, f_0)$  above is restricted to  $f_0 \geq 0$  and is, in fact, equal to

$$[S(\ell, m, f_0) + S(-\ell, -m, -f_0)],$$

$$S(\ell, m, f_0) = S(-\ell, -m, -f_0)$$

where

(3.2)

if  $\eta(x, y, t)$  is to be real.

Let us see how  $S'(\ell, m, f)$  might be found: we have said that  $\eta(x, y, t)$  can be assumed to be a stationary Gaussian process. One characteristic of such a process is that for fixed values  $(x_0, y_0, t_0)$  of the process indices,  $\eta(x_0, y_0, t_0)$  is random variable with a Gaussian distribution; i.e.,

$$\text{Prob}(\eta(x_0, y_0, t_0) < \eta_0) = \int_{-\infty}^{\eta_0} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\eta-\mu}{\sigma}\right)^2} d\eta$$

where  $\mu$  is the arithmetic mean of  $\eta$  and  $\sigma^2$  is the variance. Intuitively  $\eta$  is as likely to be positive as negative, so let us assume that  $\text{Prob}(\eta(x_0, y_0, t_0) < 0) = 1/2$ . Since  $\eta$  is Gaussian distributed, and is thus symmetric about its mean, we have  $\text{Prob}(\eta(x_0, y_0, t_0) < \mu) = 1/2$  or that  $\mu = 0$ . For  $\sigma^2$ , we have (using expected value notation)

$$\sigma^2 = E[(\eta - \mu)^2] = E[\eta^2(x_0, y_0, t_0)]$$

where we are thinking of  $\eta$  as a random variable.

A Gaussian process is completely defined statistically if we know the form of the mean

$E(\eta(x, y, t))$  and the covariances

$$E\{[\eta(x, y, t) - E(\eta(x, y, t))][\eta(x+X, y+Y, t+T) - E(\eta(x+X, y+Y, t+T))]\},$$

where  $X$ ,  $Y$ , and  $T$  are space and time separations, respectively. Refer to Parzen (1962 - pages 88-89). We have assumed  $E(\eta(x, y, t)) = \mu = 0$  and that the process is stationary (only weakly stationary is necessary). Hence, by definition of weak stationarity, we have for each  $(x, y, t)$ , and yet independent of the particular  $x, y, t$  values, the covariance form

$$R(X, Y, T) \equiv E[\eta(x, y, t) \eta(x+X, y+Y, t+T)] \quad (3.3)$$

All of the properties of the stationary Gaussian process  $\eta(x, y, t)$  are implicit in  $R(X, Y, T)$ , just as a knowledge of  $\mu$  and  $\sigma^2$  for a single Gaussian random variable completely defines such a random variable. Here it is important to understand that we are discussing expected values across all possible realizations at a point  $(x, y, t)$ ; i.e., across the ensemble of all possible sea wave shapes at  $(x, y, t)$  for a given  $S(\ell, m, f)$ .

There is a simple and unique relationship between  $R(x, y, t)$  and  $S(\ell, m, f)$ . Consider a single real wave element (from Equation (2.16) and (3.2)) as a random process and write  $\eta(x, y, t) = [\text{EXP}(i2\pi(\ell x + m y + f t + \alpha))$

$$+ \text{Exp}(-i2\pi(\ell x + m y + f t + \alpha))] \sqrt{S(\ell, m, f)} d\ell dm df.$$

Form the covariance function

$$\begin{aligned}
 R(X,Y,T) &= E[\eta(x,y,t) \cdot \eta(x+X,y+Y,t+T)] \\
 &= E[\exp(i2\pi(l(2x+X)+m(2y+Y)+f(2t+T)+2\alpha)) \\
 &\quad + \exp(-i2\pi(l(2x+X)+m(2y+Y)+f(2t+T)+2\alpha)) \\
 &\quad + \exp(i2\pi(lX+mY+fT)) \\
 &\quad + \exp(-i2\pi(lX+mY+fT))] S(l,m,f) dl dm df
 \end{aligned}$$

where E is the expected value over the ensemble for any fixed x,y,t.  
Note that

$$\sqrt{S(l,m,f) dl dm df}$$

is a constant with respect to the expected value.

Consider the following problem. Let u be a random variable with uniform probability density function

$$f(u) = \begin{cases} K & 0 \leq u < 2\pi \text{ radians} \\ 0 & \text{elsewhere} \end{cases}$$

Define a random variable  $Z = e^{iu}$ . The expected value of Z is defined as

$$\begin{aligned}
 E(Z) &= \int_{-\infty}^{\infty} e^{iu} f(u) du \\
 &= K \int_0^{2\pi} e^{iu} du = 0
 \end{aligned}$$

Considering the random variable nature of the phase  $2\pi\alpha$  as described following Equation (2.17) at the end of Section 2, and applying the above notion to the cross product terms of  $R(X,Y,T)$  we obtain

$$\begin{aligned}
 R(X,Y,T) &= [\exp(i2\pi(lX+mY+fT)) + \\
 &\quad \exp(-i2\pi(lX+mY+fT))] S(l,m,f) dl dm df.
 \end{aligned}$$

For a real wave element we have, where  $S(l,m,f) = S(-l,-m,-f)$ , see Equation (3.2),  $R(X,Y,T) = \text{Exp}(i2\pi(lX + mY + fT)) S(l,m,f) dl dm df$

$$+ \text{Exp}(-i2\pi(lX + mY + fT)) S(-l,-m,-f) dl dm df$$

which is simply the sum of the covariance functions of two complex wave elements which are conjugate pairs. It also follows that  $R(X,Y,T)$  is real valued.

Reverting to the complex wave element form, and noting that the expected ensemble value of cross products between different wave elements is zero in a manner similar to the case of cross products shown above, we obtain the composite general relationship

$$R(X,Y,T) = \iiint_{-\infty}^{\infty} \text{Exp}(i2\pi(lX + mY + fT)) S(l,m,f) dl dm df \quad (3.4)$$

We have demonstrated, but not rigorously proven, that the covariance function  $R(X,Y,T)$  is the three-dimensional Fourier transform of the directional power spectrum  $S(l,m,f)$ .

We cannot hope to be able to estimate  $R(X,Y,T)$  for continuous values of  $X$ ,  $Y$ , and  $T$ . However, there is a way around this problem, we can write the above as

$$R(X,Y,T) = \int_{-\infty}^{\infty} \text{Exp}(i2\pi fT) \left[ \iiint_{-\infty}^{\infty} \text{Exp}(i2\pi(lX + mY)) S(l,m,f) dl dm \right] df \quad (3.5)$$

which is in the form of a single dimension (variable  $f$ ) Fourier transform of the term in brackets  $[ ]$ 's. Note this term is not a function of  $T$ . It depends only on the value of  $(X,Y)$ . Further, by Fourier transform pairs we can write this expression as

$$[ ]'_s = \int_{-\infty}^{\infty} R(X,Y,T) \text{Exp}(-i2\pi fT) dT \quad (3.6)$$

In general, assuming that the term in  $[ ]$ 's is complex, we can write

$$[C(X,Y,f) - iQ(X,Y,f)] = \int_{-\infty}^{\infty} R(X,Y,T) \text{Exp}(-i2\pi fT) dT \quad (3.7)$$

To find  $[C(X,Y,f) - iQ(X,Y,f)]$  we need only know  $R(X,Y,T)$  for continuous  $T$  for the given value of  $(X,Y)$ . Further, we have just stated that

$$[C(X,Y,f) - iQ(X,Y,f)] = [ ]'_s = \iint_{-\infty}^{\infty} S(l,m,f) \exp(i2\pi(lX+mY)) dl dm \quad (3.8)$$

This is in the form of a Fourier transform; thus, we can write from transform pairs

$$S(l,m,f) = \iint [C(X,Y,f) - iQ(X,Y,f)] \exp(-i2\pi(lX+mY)) dXdY \quad (3.9)$$

As has been stated, we cannot hope to have a continuous set of values of  $(X,Y)$ . The solution is to find  $R(X,Y,T)$  for continuous  $T$  and selected values of  $(X,Y)$ , and then employ the above to estimate  $S(l,m,f)$ . This is described in the next section.

#### 4. CROSS SPECTRAL MATRIX OF AN ARRAY

Let us look at  $\eta(x,y,t)$  at two fixed points in space, say  $(x_0, y_0)$  and  $(x_1, y_1)$ . This would give two stationary Gaussian processes indexed on time alone because  $(x_0, y_0)$  and  $(x_1, y_1)$  are fixed. Thus, we may write

$$\eta_0(t) = \eta(x_0, y_0, t) \quad \text{and} \quad \eta_1(t) = \eta(x_1, y_1, t)$$

If  $X = (x_1 - x_0)$  and  $Y = (y_1 - y_0)$  Then we can say, since  $\eta(x,y,t)$  is assumed weakly stationary (see Equation (3.3)), that

$$R(X,Y,T) = E[\eta_0(t) \cdot \eta_1(t+T)]$$

where the expected value is over the ensemble for some specific value of  $t$ , where  $-\infty < t < \infty$ . Let us extend this idea by a change of notation and let  $N(X,Y,t)$  be a two-dimensional (vector) process, double-indexed on time; i.e., let  $N$  be a vector function

$$N(X,Y,t) = (\eta_0(t), \eta_1(t)) = N(t) \quad \text{for } -\infty < t < \infty \quad (4.1)$$



We can then write a generalized covariance function (assumed to be finite) as the matrix equation

$$\begin{aligned}
 R(T) &= E[N^T(t) N(t+T)] \\
 &= \begin{bmatrix} E(\eta_0(t) \eta_0(t+T)) & E(\eta_0(t) \eta_1(t+T)) \\ E(\eta_1(t) \eta_0(t+T)) & E(\eta_1(t) \eta_1(t+T)) \end{bmatrix} \\
 &= \begin{bmatrix} R(0,0,T) & R(X,Y,T) \\ R(-X,-Y,T) & R(0,0,T) \end{bmatrix} \quad (4.2)
 \end{aligned}$$

Now  $R(-T)$  is

$$R(-T) = \begin{bmatrix} R(0,0,-T) & R(X,Y,-T) \\ R(-X,-Y,-T) & R(0,0,-T) \end{bmatrix}$$

and  $R(-T)$  transpose is

$$R^T(-T) = \begin{bmatrix} R(0,0,-T) & R(-X,-Y,-T) \\ R(X,Y,-T) & R(0,0,-T) \end{bmatrix} \quad (4.3)$$

We have by Equation (3.3) and stationarity that

$$\begin{aligned}
 R(-X,-Y,-T) &= E(\eta(x_1, y_1, t+T) \eta(x_0, y_0, t)) \\
 &= E(\eta(x_0, y_0, t) \eta(x_1, y_1, t+T)) = R(X,Y,T) \quad (4.4)
 \end{aligned}$$

It then follows that

$$R(T) = R^T(-T) \quad (4.5)$$

From Equation (3.7),

$$\text{let } P^*(X,Y,f) = [C(X,Y,f) - iQ(X,Y,f)]$$

and we get

$$P^*(X,Y,f) = \int_{-\infty}^{\infty} R(X,Y,T) \exp(-i2\pi fT) dT.$$

Now  $R(-X,-Y,T) = R(X,Y,-T)$  by Equation (4.5). Thus, we have from Equation (3.4)

$$R(X,Y,-T) = \iiint_{-\infty}^{\infty} \exp(i2\pi(lX + mY + f(-T))) S(l,m,f) dl dm df$$

or, by the same procedure, that Equation (3.6) was obtained from Equation (3.4), we have

$$P^*(X,Y,f) = \int_{-\infty}^{\infty} R(X,Y,-T) \exp(i2\pi fT) dT \quad (4.6)$$

Now, since  $R(X,Y,-T)$  is real and Fourier transform pairs are unique, we must have from Equation (4.6) that

$$\int_{-\infty}^{\infty} R(X,Y,-T) \exp(-i2\pi fT) dT = P(X,Y,f)$$

a parallel form of Equation (3.6). Therefore, the Fourier transform of  $R(-X,-Y,T) = R(X,Y,-T)$  is the complex conjugate of the transform of  $R(X,Y,T)$ ; i.e., (see Equation (3.7))

$$P^*(-X,-Y,f) = [P^*(X,Y,f)]^* = P(X,Y,f)$$

In general, we have that the Fourier transform of  $R(T) = R^T(-T)$  is

$$\begin{bmatrix} P(0,0,f) & P^*(X,Y,f) \\ P(X,Y,f) & P(0,0,f) \end{bmatrix} \quad (4.7)$$

Note:  $P^*(0,0,f) = P(0,0,f)$  is real.

By definition it follows that

$$C(X,Y,f) = \text{Re}[P(X,Y,f)]$$

$$Q(X,Y,f) = \text{Im}[P(X,Y,f)]$$

where  $-\infty < f < \infty$ .

The function  $C(X,Y,f)$  is called the cospectrum and  $Q(X,Y,f)$  is called the quadrature spectrum. Both are spectral density functions.

Explicitly, we can think of  $(x_0, y_0)$  and  $(x_1, y_1)$  as being the location of elements of a probe-array with space separation  $(X,Y)$ .

The first step to find (or estimate)  $S(l,m,f)$  (see Equation (3.9)) is to find  $P(X,Y,f)$  related to a pair of array elements. This is a problem of estimating the cospectrum and quadrature spectrum of a two-dimensional (vector) stationary Gaussian process. Goodman (Mar 1967 - Chapter 3) has an excellent treatment of this subject, which we will discuss. Kinsman (1965 - Chapters 7-9) also discusses the subject. The essence of the problem is that if  $P(X,Y,f)$  is continuous and negligible for  $|f| > f_n$ , then  $R(X,Y,T)$  can be obtained by a time average over a particular realization  $N(X,Y,t)$  instead of having to average (find the expected value) over the ensemble. This says that we can find  $R(X,Y,T)$  by obtaining two time series (realizations)  $r_0(t)$  and  $r_1(t)$  measured over time at only two points; e.g.,  $(x_0, y_0)$  and  $(x_1, y_1)$  where  $(x_1 - x_0) = X$  and  $(y_1 - y_0) = Y$ . The relationship between  $(r_0(t), r_1(t))$  and  $R(X,Y,T)$   $-\infty < T < \infty$  is

$$R(X,Y,T) = \lim_{t_0 \rightarrow \infty} \frac{1}{t_0} \int_{-t_0/2}^{t_0/2} r_0(t) \cdot r_1(t+T) dt \quad (4.8)$$

where  $r_0(t)$  is a realization measured over time at  $(x_0, y_0)$  and  $r_1(t)$  is measured at  $(x_1, y_1)$ . We can simplify the notation by an expression for a time average given by

$$R(X,Y,T) = R_{01}(T) = \overline{r_0(t)r_1(t+T)}.$$

It follows from Equation (3.7) that  $C(X,Y,f) = C_{01}(f) =$

$$\int_{-\infty}^{\infty} R_{01}(T) \cos(2\pi fT) dt,$$

and

$$Q(X,Y,f) = Q_{01}(f) = \int_{-\infty}^{\infty} R_{01}(T) \sin(2\pi fT) dT. \quad (4.9)$$

We also have (see Equations (4.2) and (4.7))  $C_{00}(f) = C_{11}(f) = P_{00}(f) = P_{11}(f)$ ,

$$Q_{00}(f) = Q_{11}(f) = 0;$$

$$P_{01}^*(f) = C_{01}(f) - i Q_{01}(f). \quad (4.10)$$

The phase of  $P_{01}(f)$  is given by

$$Q_{01}(f) = \text{Arctan} \frac{Q_{01}(f)}{C_{01}(f)}. \quad (4.11)$$

This is the expected phase lead of the signal at  $(x_0, y_0)$  over the signal at  $(x_1, y_1)$  for  $f$  where  $-\infty < f < \infty$ .

For an array of  $N$  detectors located at  $(x_1, y_1)$ ,  $(x_2, y_2)$ ,  $(x_3, y_3)$  ...  $(x_N, y_N)$  we can find  $N^2$  spectra  $[P_{ij}]$   $i = 1, N, j = 1, N$ . This gives a unique spectrum  $P_{ii}$  ( $P_{11} = \dots = P_{NN}$ ) and since  $P_{ij} = P_{ji}^*$  (see Equation (4.6) and 4.7))

we have

$$\frac{N(N-1)}{2} \quad (4.12)$$

unique cross spectra or a total of  $[N(N-1) + 2]/2$  unique spectra. Thus, for real  $\eta(x,y,t)$  we have  $P_{ij}(f) = P_{ji}^*(f)$  and  $P_{ij}(f) = P_{ji}^*(-f)$  allowing us to define the information about  $P(X,Y,f)$  obtainable from an array by a cross spectral matrix

$$\begin{pmatrix} P_{11}(f) & C_{12}(f) & \dots & C_{1N}(f) \\ Q_{12}(f) & P_{22}(f) & \dots & C_{2N}(f) \\ \vdots & \vdots & \ddots & \vdots \\ Q_{1N}(f) & \dots & \dots & P_{NN}(f) \end{pmatrix} \quad \text{WHERE } 0 \leq f < \infty \quad (4.13)$$

This information can be used together with Equation (3.9) to obtain an approximation to  $S(l,m,f)$ . Numerical details for finding the spectral matrix are given in Bennett, et al (June 1964).

It should be pointed out that negative frequencies are still considered in the relationships being discussed. We do not know  $P^*(X,Y,f)$  for continuous values of  $(X,Y)$ . We do know from the spectral matrix the values of

$$P^*(X_{ij}, Y_{ij}, f) \text{ for } i = 1, \dots, N; j = 1, \dots, N$$

where  $X_{ij} = (x_j - x_i)$

$$Y_{ij} = (y_j - y_i) .$$

We also have from Equation (4.7) that

$$P^*(-X_{ij}, -Y_{ij}, f) = P(X_{ij}, Y_{ij}, f) . \quad (4.14)$$

From Equation (3.9) we get

$$S(l,m,f) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \{ P^*(X,Y,f) \cos[2\pi(lX+mY)] \\ - i P^*(X,Y,f) \sin[2\pi(lX+mY)] \} dX dY$$

or, since  $S(l,m,f)$  is real

$$S(l,m,f) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \{ C(X,Y,f) \cos[2\pi(lX+mY)] \\ - Q(X,Y,f) \sin[2\pi(lX+mY)] \} dX dY \quad (4.15)$$

Let us consider treating the points of  $(X,Y)$  where we know  $C(X,Y,f)$  and  $Q(X,Y,f)$  as weighted Dirac delta functions; e.g., at  $(X_{12}, Y_{12})$  we get

$$C(X,Y,f) = b_{12} C(X_{12}, Y_{12}, f) \delta(X - X_{12}) \delta(Y - Y_{12}) .$$

Reverting to the  $C_{ij}$ ,  $Q_{ij}$  notation of Equation (4.13), we have, where  $X_{ji} = -X_{ij}$  and  $Y_{ji} = -Y_{ij}$ ,  $C_{ji} = C_{ij}$  and  $Q_{ji} = -Q_{ij}$ . The numerical form of Equation (4.15) then becomes

$$S(\ell, m, f) = b_{11} C_{11}(f) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N b_{ij} \left\{ C_{ij}(f) \cos [2\pi (\ell X_{ij} + m Y_{ij})] - Q_{ij}(f) \sin [2\pi (\ell X_{ij} + m Y_{ij})] \right\}. \quad (4.16)$$

Choice of  $b_{ij}$  values is arbitrary. A reasonable choice is  $b_{ij} = [N(N-1) + 1]^{-1}$  for all  $(i, j)$  (refer to following section). We now have a basis for an approximation of  $S(\ell, m, f)$ . Before exploiting this result, we need a few side results.

## 5. SPECIAL CROSS SPECTRAL MATRICES

Assume that we have a real sea wave of frequency  $f_0 > 0$  moving from direction  $\theta_0$  where  $\ell_0 = K_0 \cos \theta_0$  and  $m_0 = K_0 \sin \theta_0$ ,  $K_0$  being the wave number from Equation (3.1). We can write the wave as

$$\eta(x, y, t) = A \cos(2\pi (\ell_0 x + m_0 y + f_0 t + \alpha)) \quad (5.1)$$

Since the root-mean-square (rms) value of a cosine wave is  $A/\sqrt{2}$ , we have for the two-sided  $(-\infty < f < \infty)$  directional power spectrum of the wave in Equation (5.1)

$$S(\ell, m, f) = \frac{A^2}{4} \left[ \delta(\ell - \ell_0) \delta(m - m_0) \delta(f - f_0) + \delta(\ell + \ell_0) \delta(m + m_0) \delta(f + f_0) \right] \quad (5.2)$$

or in polar form where  $K = \sqrt{\ell^2 + m^2}$ ;  $\theta = \arctan(\frac{m}{\ell})$

$$S(K, \theta, f) = \frac{A^2}{4} \left[ \delta(\theta - \theta_0) \delta(f - f_0) + \delta(\theta - (\theta_0 - \pi)) \delta(f + f_0) \right] \delta(K - K_0)$$

From Equations (3.8) and (5.2) we have for a single wave of frequency  $f_0 > 0$  from a direction  $\theta_0$  that the two-sided

$$\begin{aligned}
 P_{ij}^*(f) &= \frac{A^2}{4} \left[ \exp(i 2\pi (l_0 X_{ij} + m_0 Y_{ij})) \delta(f - f_0) + \right. \\
 &\quad \left. + \exp(i 2\pi (-l_0 X_{ij} - m_0 Y_{ij})) \delta(f + f_0) \right] \\
 \text{or where } P_{ij}^*(f) &= C_{ij}(f) - i Q_{ij}(f) \quad \text{that} \\
 C_{ii}(f_0) &= C_{ii}(-f_0) = \frac{A^2}{4}, \\
 C_{ij}(f_0) &= C_{ij}(-f_0) = \frac{A^2}{4} \cos(2\pi (l_0 X_{ij} + m_0 Y_{ij})), \\
 Q_{ij}(f_0) &= -Q_{ij}(-f_0) = -\frac{A^2}{4} \sin(2\pi (l_0 X_{ij} + m_0 Y_{ij})) \quad (5.3)
 \end{aligned}$$

describe the elements for the spectral matrix of a single wave. Recall that, in general,  $C_{ij}(f) = C_{ji}(f)$  and  $Q_{ij}(f) = -Q_{ji}(-f)$ . Substituting into Equation (4.16), we get where  $b_{ij} = [N(N-1)+1]^{-1} = 1/M$  (5.4)

$$\begin{aligned}
 \text{and } f_0 > 0 \text{ is assumed } S(l, m, f_0) &\doteq \frac{A^2}{4M} \left\{ 1 + \right. \\
 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N &\left[ \cos(2\pi (l_0 X_{ij} + m_0 Y_{ij})) \cos(2\pi (l X_{ij} + m Y_{ij})) + \right. \\
 &\left. + \sin(2\pi (l_0 X_{ij} + m_0 Y_{ij})) \sin(2\pi (l X_{ij} + m Y_{ij})) \right] \quad \text{or}
 \end{aligned}$$

$$\begin{aligned}
 S(l, m, f_0) &\doteq \\
 \frac{A^2}{4M} &\left\{ 1 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \cos(2\pi [X_{ij}(l - l_0) + Y_{ij}(m - m_0)]) \right\} \quad (5.5)
 \end{aligned}$$

The choice of  $b_{ij} = 1/M = [N(N-1)+1]^{-1}$  and observing that  $\sum_{i=1}^{N-1} \sum_{j=i+1}^N 1 = \frac{N(N-1)}{2}$ ,

gives the convenient result (Note: For  $-f_0 < 0$  we would use  $(-l_0, -m_0)$  in place of  $(l_0, m_0)$ )

$$S(l_0, m_0, f_0) = S(-l_0, -m_0, -f_0)$$

$$\doteq \frac{A^2}{4m} \left\{ 1 + N(N-1) \right\} = \frac{A^2}{4}$$

which agrees with the values of Equation (5.2) at the points  $(l_0, m_0, f_0)$  and  $(-l_0, -m_0, -f_0)$ . Note that there is not general agreement elsewhere. In fact, Equation (4.16) may (and does) give negative values for the approximation of  $S(l, m, f)$ . This is a problem of probe array design and is directly related to the directional resolving power of a probe array. This problem is discussed later in another section.

Consider the case of a single frequency,  $f_0 > 0$ , real sea with equal wave energy from all directions; i.e., isotropic waves. In this case, assuming the wave equation (Equation (3.1)) holds, we have

$$S(l, m, f) = [\tilde{A} \delta((l^2 + m^2) - (l_0^2 + m_0^2))] [\delta(f - f_0) + \delta(f + f_0)]$$

OR WHERE  $K^2 = l^2 + m^2$ ,  $K = +\sqrt{K^2}$ , AND  $\theta = \text{ARCTAN}(m/l)$

$$S(K, \theta, f) = \tilde{A} \delta(K^2 - K_0^2) [\delta(f - f_0) + \delta(f + f_0)] \quad (5.6)$$

as the two-sided directional power spectrum for such an isotropic wave.

Since  $l = K \cos \theta$  and  $m = K \sin \theta$ , Equation (3.8) can be expressed in polar coordinate form as

$$P_{ij}^*(f) = \int_{-\pi}^{\pi} \int_0^{\infty} S(K, \theta, f) \exp(i 2\pi K (X_{ij} \cos \theta + Y_{ij} \sin \theta)) K dK d\theta \quad (5.7)$$

Letting  $D_{ij} = (X_{ij}^2 + Y_{ij}^2)$



and  $\phi_{ij} = \text{ARCTAN} \left( \frac{Y_{ij}}{X_{ij}} \right)$

we can write

$$P_{ij}^*(f) = \int_{-\pi}^{\pi} \int_0^{\infty} S(K, \theta, f) \exp(i 2\pi K D_{ij} \cos(\theta - \phi_{ij})) K dk d\theta \quad (5.8)$$

Using Equation (5.6) for  $S(K, \theta, f)$  we get

$$\begin{aligned} P_{ij}^*(f) &= \tilde{A} K_0 \int_{-\pi}^{\pi} \exp(i 2\pi K_0 D_{ij} \cos(\theta - \phi_{ij})) d\theta \\ &= \tilde{A} K_0 \int_{-\pi}^{\pi} \cos(2\pi K_0 D_{ij} \cos(\theta - \phi_{ij})) d\theta + \\ &\quad + i \tilde{A} K_0 \int_{-\pi}^{\pi} \sin(2\pi K_0 D_{ij} \cos(\theta - \phi_{ij})) d\theta \end{aligned} \quad (5.9)$$

Now, departing from the above development, consider the following integral where

$$\begin{aligned} z &= 2\pi K_0 D_{ij} ; \quad \psi = \phi_{ij} \\ &\int_{-\pi}^{\pi} \cos(n\theta) \cos(z \cos(\theta - \psi)) d\theta \end{aligned}$$

Let  $\phi = \theta - \psi$  and we get

$$\int_{-\pi-\psi}^{\pi-\psi} \cos(n\phi + n\psi) \cos(z \cos \phi) d\phi$$

Expanding  $\cos(n\theta + n\psi)$  we get

$$\begin{aligned} & \cos n\psi \int_{-\pi-\psi}^{\pi-\psi} \cos n\phi \cos(z \cos \phi) d\phi \\ & - \sin n\psi \int_{-\pi-\psi}^{\pi-\psi} \sin n\phi \cos(z \cos \phi) d\phi . \end{aligned}$$

We have  $(\pi - \psi) - (-\pi - \psi) = 2\pi$  so that the integrands are over  $2\pi$  allowing us to write the above as

$$\begin{aligned} & \cos n\psi \int_{-\pi}^{\pi} \cos n\phi \cos(z \cos \phi) d\phi \\ & - \sin n\psi \int_{-\pi}^{\pi} \sin n\phi \cos(z \cos \phi) d\phi . \end{aligned}$$

From Ryzhik and Gradshteyn (1965 - page 402) we have (since sine is odd and cosine is even) the result

$$\begin{aligned} & \int_{-\pi}^{\pi} \cos(n\theta) \cos(z \cos(\theta - \psi)) d\theta \\ & = \cos n\psi \left[ 2\pi \cos\left(\frac{n\pi}{2}\right) J_n(z) \right] . \end{aligned} \tag{5.10}$$

In a similar way we get

$$\begin{aligned} & \int_{-\pi}^{\pi} \cos(n\theta) \sin(z \cos(\theta - \psi)) d\theta \\ & = \cos n\psi \left[ 2\pi \sin\left(\frac{n\pi}{2}\right) J_n(z) \right] , \end{aligned} \tag{5.11}$$

where  $J_n(z)$  is a Bessel function of the first kind of integer order  $n$ . Returning to Equation (5.9), the above results give, for  $n = 0$  where  $f_0 > 0$ , the result

$$P_{ij}(\pm f_0) = \tilde{A} 2\pi K_0 J_0(2\pi K_0 D_{ij})$$

Since the above is real

$$C_{ii}(\pm f_0) = 2\pi K_0 \tilde{A}$$

$$C_{ij}(\pm f_0) = 2\pi K_0 \tilde{A} J_0(2\pi K_0 D_{ij})$$

$$Q_{ij}(\pm f_0) = 0 \quad (5.12)$$

describe the elements for the spectral matrix of a single frequency isotropic sea.

The above two special cases for sea waves are the extremes of directionality of real sea waves of frequency  $f_0 > 0$ . These results will have important applications later.

## 6. A MEASURE OF ARRAY DIRECTIONAL RESOLVING POWER

From Equation (3.9) we have the Fourier transform

$$S(l, m, f) = \iint_{-\infty}^{\infty} P^*(X, Y, f) \exp(-i 2\pi (lX + mY)) dx dy \quad (6.1)$$

In practice we use a probe array with elements at  $(x_1, y_1), \dots, (x_k, y_k)$  to obtain  $P^*(X, Y, f)$  at the separation points  $(0, 0)$ ,  $(x_{12}, y_{12})$ ,  $(-x_{12}, -y_{12}), \dots, (x_{k-1, k}, y_{k-1, k})$ ,  $(-x_{k-1, k}, -y_{k-1, k})$ .

We do not then know  $P^*(X, Y, f)$  but the product

$$[P^*(X, Y, f) g(X, Y)] \quad (6.2)$$

where  $g(X,Y)$  is a set of Dirac delta functions standing on the separation points of the probe array and zero elsewhere.

Thus, we have the estimate

$$\hat{S}(\ell, m, f) = \iint_{-\infty}^{\infty} [P^*(X, Y, f) g(X, Y)] \exp(-i 2\pi(\ell X + m Y)) dX dY$$

Let

$$G(\ell, m) = \iint_{-\infty}^{\infty} g(X, Y) \exp(-i 2\pi(\ell X + m Y)) dX dY \quad (6.3)$$

Using this and Equation (3.8) we have for a given  $(\ell_0, m_0, f_0)$  that

$$\begin{aligned} \hat{S}(\ell_0, m_0, f_0) &= \iiint_{-\infty}^{\infty} \left[ \iint_{-\infty}^{\infty} S(\ell, m, f_0) \exp(i 2\pi(\ell X + m Y)) d\ell dm \right] g(X, Y) \\ &\quad \exp(-i 2\pi(\ell_0 X + m_0 Y)) dX dY \\ &= \iiint_{-\infty}^{\infty} \left[ \iint_{-\infty}^{\infty} S(\ell, m, f_0) g(X, Y) \exp(-i 2\pi(X(\ell_0 - \ell) + Y(m_0 - m))) dX dY \right] d\ell dm \\ &= \iint_{-\infty}^{\infty} S(\ell, m, f_0) \left[ \iint_{-\infty}^{\infty} g(X, Y) \exp(-i 2\pi(X(\ell_0 - \ell) + Y(m_0 - m))) dX dY \right] d\ell dm \\ &= \iint_{-\infty}^{\infty} S(\ell, m, f_0) G(\ell_0 - \ell, m_0 - m) d\ell dm \end{aligned} \quad (6.4)$$

As expected,  $\hat{S}(\ell, m, f)$  is a two-dimensional convolution of the true directional spectrum  $S(\ell, m, f)$  with  $G(\ell, m)$  the Fourier transform of  $g(X, Y)$ . We see then that  $\hat{S}(\ell, m, f)$  is a weighted average of  $S(\ell, m, f)$

and that  $G(l, m)$  is a measure of the directional resolving power of the assumed probe array. By the nature of  $g(X, Y)$  we have from Equation (6.3)

$$G(l, m) = 1 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \cos(2\pi(l X_{ij} + m Y_{ij})) \quad (6.5)$$

If we assume that the wave equation (Equation (3.1)) holds, we find that  $S(l, m, f_0)$  is zero when  $l^2 + m^2 \neq K_0^2$ , the wave number for  $f_0$ . From this we have for a given  $(l_0, m_0)$  that the directional resolving power, DRP, is

$$\text{DRP}(l, m, f_0) = \iint_{-\infty}^{\infty} \iint_{-\infty}^{\infty} ((l^2 + m^2) - K_0^2) G(l_0 - l, m_0 - m) dl dm$$

$$\text{LET } l = K_0 \cos \theta, \quad m = K_0 \sin \theta, \text{ WHICH IMPLIES } l^2 + m^2 = K_0^2.$$

and we get, for energy coming from a direction  $\theta_0$  at frequency  $f_0$  as a function of  $0 \leq \theta \leq 2\pi$ , that

$$\text{DRP}(\theta | \theta_0, f_0) = G(K_0(\cos \theta_0 - \cos \theta), K_0(\sin \theta_0 - \sin \theta)).$$

From Equation (6.5) we get

$$\text{DRP}(\theta | \theta_0, f_0) = 1 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \cos \left[ 2\pi (X_{ij} K_0 (\cos \theta_0 - \cos \theta) + Y_{ij} K_0 (\sin \theta_0 - \sin \theta)) \right]$$

$$= 1 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \cos \left[ 2\pi ((l_0 - K_0 \cos \theta) X_{ij} + (m_0 - K_0 \sin \theta) Y_{ij}) \right]$$

$$\text{NOTE THAT } \text{DRP}(\theta_0 | \theta_0, f_0) = N(N-1) + 1 \quad (6.6)$$

Compare Equation (6.6) and (5.5). Except for the amplitude term,  $A^2/4M$ , in Equation (5.5) the equations give identical results. The choice of  $b_{ij} = [N(N-1) + 1]^{-1} = 1/M$  is again found convenient.

## 7. DIRECTIONAL ANALYSIS FROM THE CROSS SPECTRAL MATRIX

First, we consider a fundamental approach. We have for a pair of detectors I and J located at  $(x_i, y_i)$  and  $(x_j, y_j)$  respectively, the cross spectral matrix,  $P_{ij}(f) = C_{ij}(f) + iQ_{ij}(f)$  and more importantly  $\phi_{ij}(f)$  the phase lead of I over J given by,

$$\phi_{ij}(f) = \text{ARCTAN} \left[ \frac{Q_{ij}(f)}{C_{ij}(f)} \right] \quad (7.1)$$

The actual phase lead may differ from this value since the true phase lead  $\theta$  is some one of the values

$$\phi_{ij}(f) + h 2\pi$$

where

$$h = 0, \pm 1, \pm 2, \dots$$

Consider a single wave of frequency  $f_0$  with corresponding wave length  $\lambda_0$  and wave number  $K_0 = 1/\lambda_0$ , and find the direction the wave must travel; i.e., fit a single wave to the spectral matrix results for the detectors I and J.

Let  $D_{ij}$  be the distance between I and J. The distance between I and J in wave lengths is  $K_0 D_{ij}$ . In radians this is  $2\pi K_0 D_{ij}$ . From this relation we get

$$-2\pi K_0 D_{ij} \leq \phi \leq 2\pi K_0 D_{ij}$$

or that only values of  $h$  such that

$$-2\pi K_0 D_{ij} \leq \phi_{ij}(f) + h 2\pi \leq 2\pi K_0 D_{ij} \quad (7.2)$$

give physically acceptable candidates for the value of  $\phi$ . If  $D_{ij} < \lambda_0/2$  only one  $h$  value is valid. If  $\lambda_0/2 < D_{ij} < \lambda_0$  at most two values of  $h$  are valid, etc.

The problem is how to find the true direction,  $\theta_0$ , of a single wave given the above possible value(s) of  $\phi$ . Consider a given value of  $\phi$  in terms of wave length units and we obtain

$$L_o = \frac{\phi}{2\pi} \lambda_o = \frac{\phi}{2\pi K_o} \quad (7.3)$$

Figure 4 illustrates a case for  $\phi \geq 0$  (and thus  $L_o \geq 0$ ). From the figure we have, where the true direction is  $\theta_o$  and true phase is  $\phi$ , that

$$\theta_o = \psi_{ij} + \frac{\pi}{2} + \alpha$$

WHERE  $\sin \alpha = \frac{\phi}{2\pi K_o D_{ij}} \quad (7.4)$

OR  $\alpha = \text{ARCSIN} \left[ \frac{\phi}{2\pi K_o D_{ij}} \right] = \text{ARCSIN} \left[ \frac{L_o}{D_{ij}} \right]$

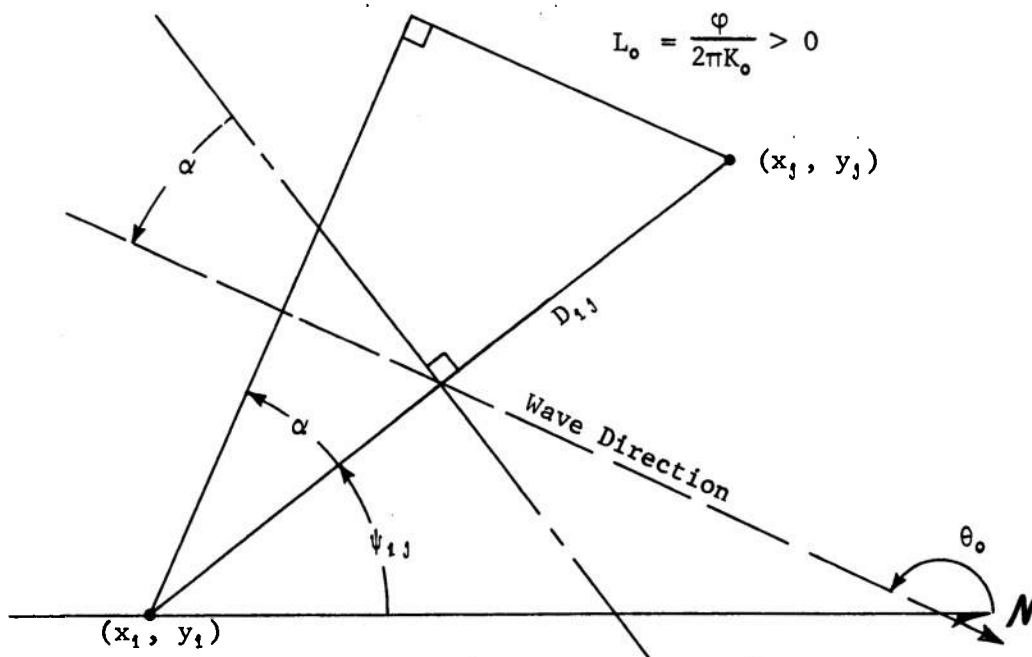


FIGURE 4. WAVE DIRECTION ANALYSIS

Recall that  $\sin(\alpha) = \sin(\pi - \alpha)$ . Thus for a given  $\phi \geq 0$  we get, since  $\alpha$  must be obtained from an arcsin relationship, two possible values of wave direction, the true value  $\theta_0$  and its image

$$\begin{aligned}\theta' &= \left[ \psi_{ij} + \frac{\pi}{2} \right] + \left[ -\pi - \alpha \right] \\ &= \psi_{ij} - \frac{\pi}{2} - \alpha = \psi_{ij} - \left[ \frac{\pi}{2} + \alpha \right]\end{aligned}\quad (7.5)$$

This is illustrated in Figure 5. In actual practice we do not know the true direction, thus a given value of  $\phi \geq 0$  gives the direction as

$$\theta_0 = \psi_{ij} \pm \left[ \frac{\pi}{2} + \alpha \right]$$

where  $0 \leq \alpha \leq \pi/2$  is obtained from the principle value of the arcsin. If  $\phi < 0$ , then I actually lags J by  $|\phi| > 0$  and  $L'_0 = L_0/D_{1j} < 0$ , so that  $\arcsin(L'_0)$  gives  $-\pi/2 \leq \alpha < 0$ .

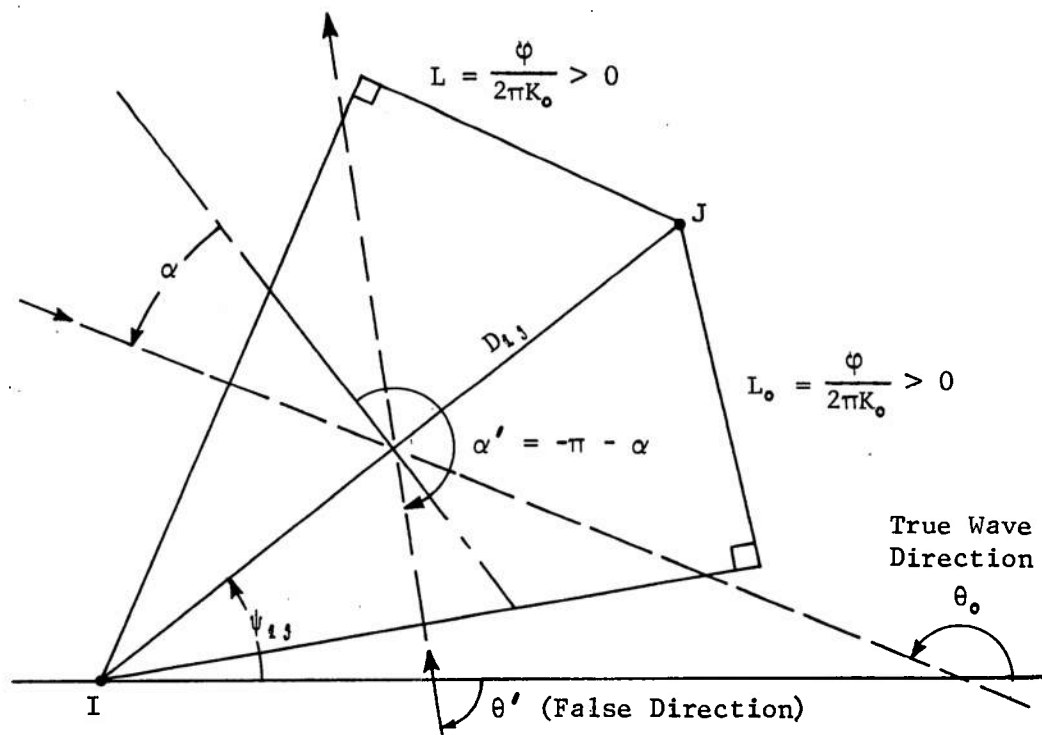


FIGURE 5. DIRECTION ANALYSIS FROM A PAIR OF ARRAY ELEMENTS



The implied directions, for  $\phi < 0$ , are directly opposite from those for  $\phi \geq 0$  so that for a given value of  $\phi \leq 0$  we get directions ( $\alpha < 0$ )

$$\text{and } \theta_o = \psi_{ij} - \frac{\pi}{2} - \alpha$$

$$\text{or } \theta_o = \psi_{ij} + \frac{\pi}{2} + \alpha$$

$$\theta = \psi_{ij} \pm \left[ \frac{\pi}{2} + \alpha \right]$$

as before.

Thus, where the principle value of arcsin is assumed, we get a set of possible directions

$$\theta_{oh} = \psi_{ij} \pm \left[ \frac{\pi}{2} + \alpha_h \right]$$

where

$$\alpha_h = \text{ARCSIN} \left[ \frac{\phi_{ij}(f) + h2\pi}{2\pi K_o D_{ij}} \right] \quad (7.6)$$

$h$  being constrained by

$$\left| \frac{\phi_{ij}(f) + h2\pi}{2\pi K_o D_{ij}} \right| \leq 1$$

An example of this type analysis, for an array pair, is illustrated in Figure 6. Thus several estimates of  $\theta_o$  are available (at least two).

The estimates of true direction,  $\theta_o$ , often vary from one array element pair to another, making the selection of a true  $\theta_o$  value difficult. The selection is also hindered because half of the estimates of  $\theta_o$  are of the image type; i.e., false estimates.

While the above directional method leaves something to be desired, it does illustrate the basic directional information produced by an array of detectors.

A better method, suggested in Munk et al (April 1963), of using the spectral matrix directional information to fit a single wave at each

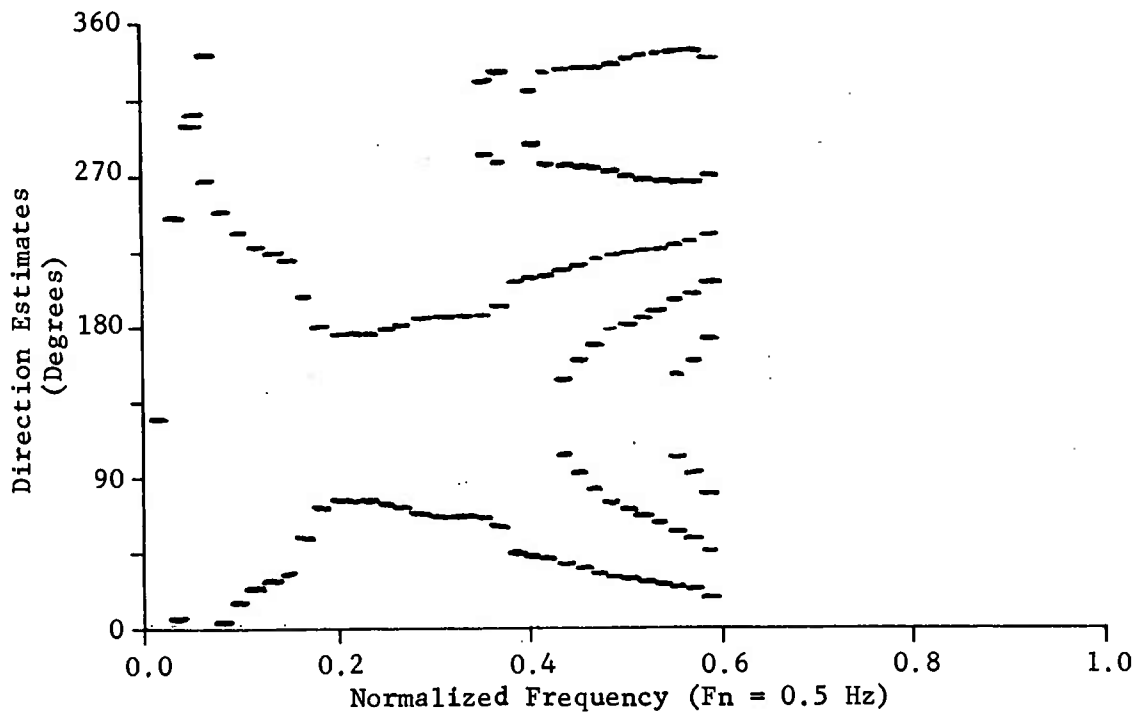


FIGURE 6. DIRECTIONAL ESTIMATES FOR A PAIR OF ARRAY ELEMENTS

frequency is given below. It is based on Equation (4.16) in the form

$$S(l, m, f) \doteq \frac{1}{M} \left[ C_o(f) + 2 \sum_{i=1}^N \sum_{j=i+1}^N \left[ C_{ij}(f) \cos(2\pi(l X_{ij} + m Y_{ij})) \right. \right. \\ \left. \left. - Q_{ij}(f) \sin(2\pi(l X_{ij} + m Y_{ij})) \right) \right] \quad (7.7)$$

where  $M = [N(N-1) + 1]$ ,  $C_o(f) = \frac{1}{N} \sum_{i=1}^N C_{ii}(f)$

and  $N$  = number of array elements.

Recall that for a single real wave of frequency  $f_0 > 0$  and known direction  $\theta_0$ ,  $C_{ij}(f_0)$ ,  $Q_{ij}(f_0)$  are known (see Equation (5.3)). These values give

$$S(k, \theta, f) = S(k, [\theta - \pi], -f) = \frac{A^2}{4} .$$

When a single, well-directed swell is expected, it is reasonable to assume a single wave for a given frequency exists, and to select  $\theta_0$  and  $A_0 = A^2/4$  such that the least square error between the theoretical cross spectral matrix for a single wave (see Equations (5.1) and (5.3)) and an observed cross spectral matrix is a minimum. Accordingly, using the expressions of Equation (5.3) and an observed cross spectral matrix for a given frequency,  $f_0$ , we can form the squared error

$$\begin{aligned} H &= (C_0 - A_0)^2 \\ &+ 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N [C_{ij} - A_0 \cos(2\pi(l_0 X_{ij} + m_0 Y_{ij}))]^2 \\ &+ 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N [Q_{ij} + A_0 \sin(2\pi(l_0 X_{ij} + m_0 Y_{ij}))]^2 \end{aligned}$$

$$\text{NOTE: } A_0 = \frac{A^2}{4} ; C_0 = \frac{1}{N} \sum_{i=1}^N C_{ii} \quad (7.8)$$

Expanding and collecting terms we get

$$\begin{aligned} H &= C_0^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N (C_{ij}^2 + Q_{ij}^2) + [N(N-1) + 1] A_0^2 \\ &- 2 A_0 \left[ C_0 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N C_{ij} \cos(2\pi(l_0 X_{ij} + m_0 Y_{ij})) \right. \\ &\left. - 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N Q_{ij} \sin(2\pi(l_0 X_{ij} + m_0 Y_{ij})) \right] \end{aligned} \quad (7.9)$$

or using results in Equation (7.7)

$$H = C_o^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N (C_{ij}^2 + Q_{ij}^2) + [N(N-1)+1] [A_o^2 - 2 A_o S(\ell, m, f_o)] \quad (7.10)$$

To find  $A_o$  that minimizes  $H$ , consider

$$\frac{\delta H}{\delta A_o} = 2 [N(N-1)+1] [A_o - S(\ell, m, f_o)] = 0 \quad (7.11)$$

This requires that  $A_o$  be of the form  $A_o = S(\ell, m, f_o)$  and a resulting value of  $H$  of the form

$$H = C_o^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N (C_{ij}^2 + Q_{ij}^2) - [N(N-1)+1] [S(\ell, m, f_o)]^2 \quad (7.12)$$

Since  $C_o^2$ ,  $C_{ij}^2$ , and  $Q_{ij}^2$  are all nonnegative, a minimum  $H$  results when  $S(\ell, m, f_o)$  is a maximum. A choice of  $\ell_o$  and  $m_o$  that maximizes  $S(\ell, m, f_o)$  implies a  $\theta_o = \arctan m_o / \ell_o$  which is optimum. Remember that we are assuming  $K_o^2 = \ell_o^2 + m_o^2$  holds, along with the wave equation. The results then for each  $f_o$  is a two-sided energy spectrum estimate  $A_o(f_o, \theta_o)$ . Appendix B contains a listing of a FORTRAN II program for finding  $A_o(f_o, \theta_o)$ , the least square wave fit, from a set of spectral matrices obtained from the task SWOC data collection and analysis system described in Bennett et al (June 1964).

Examples of least square single-wave train fit analysis from Bennett (March 1968) are shown in Figure 7.

A more complete collection of the directional spectra calculated from data collected off Panama City, Florida, is given in Appendix A, and in Bennett (November 1967), and Bennett and Austin (September 1968), an unpublished Laboratory Technical Note TN160.

We would actually like a continuous estimate of  $S'(\ell, m, f)$ . Consider then a third method. From Equation (3.8) we have for a pair of detectors, as illustrated in Figure 8, that

$$P^*(X, Y, f) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(\ell, m, f) \exp [i 2 \pi (\ell X + m Y)] d\ell dm$$

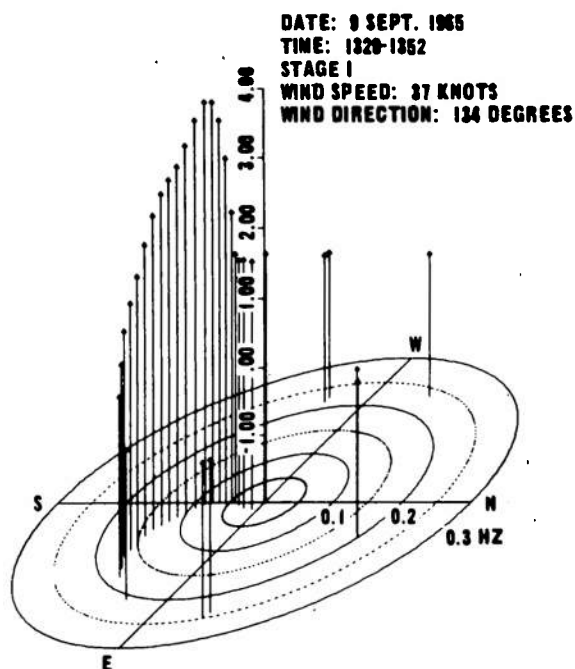


FIGURE 7A DIRECTIONAL SPECTRUM  $A_0(f, \theta)$

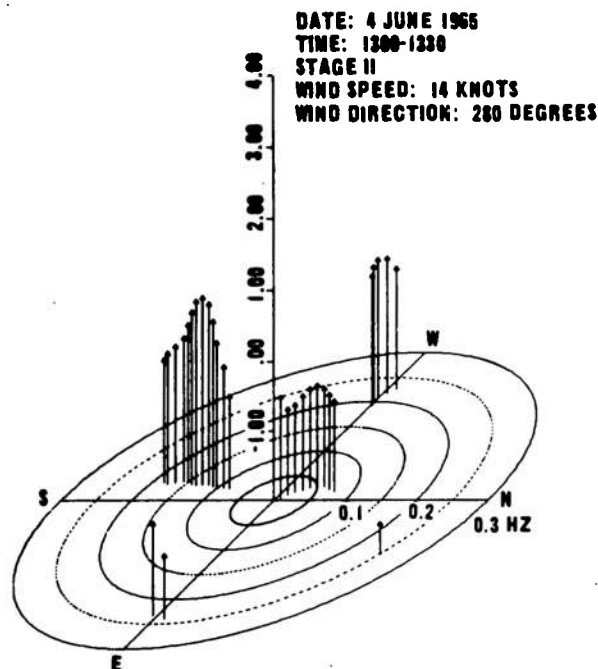


FIGURE 7B DIRECTIONAL SPECTRUM  $A_0(f, \theta)$

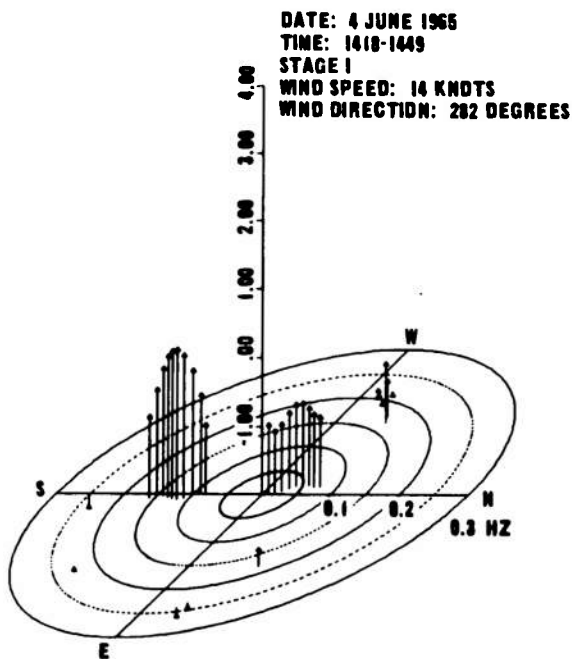


FIGURE 7C DIRECTIONAL SPECTRUM  $A_0(f, \theta)$

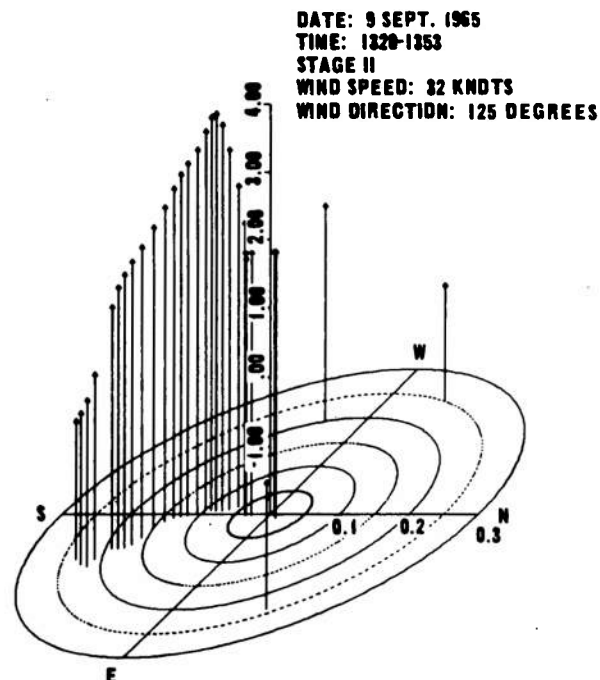


FIGURE 7D DIRECTIONAL SPECTRUM  $A_0(f, \theta)$

FIGURE 7. LEAST SQUARE SINGLE WAVE FIT DIRECTIONAL SPECTRA  $A_0(f, \theta_0)$

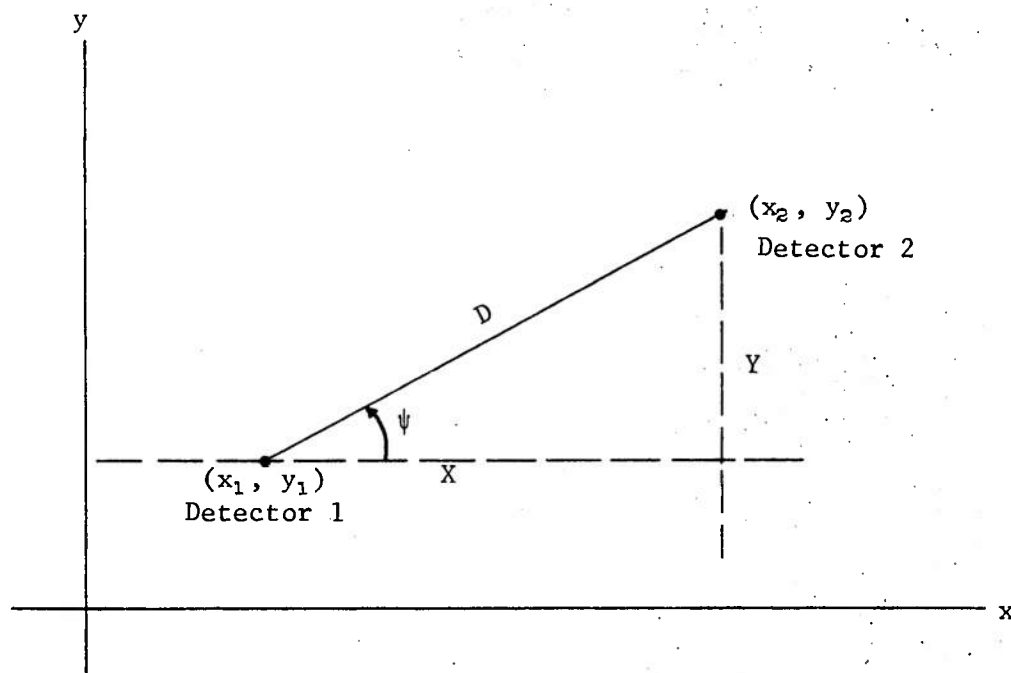


FIGURE 8. DETECTOR GEOMETRY

Let  $l = K \cos \theta$  and  $m = K \sin \theta$

and

$$D = \sqrt{X^2 + Y^2}, \psi = \text{Arctan } \frac{Y}{X}$$

or

$$X = D \cos \psi \text{ and } Y = D \sin \psi.$$

Using the above changes of variable, we get

$$P^*(X, Y, f) = \int_{-\pi}^{\pi} \int_0^{\infty} S(K, \theta, f) \exp[i2\pi(KD \cos \theta \cos \psi + K D \sin \theta \sin \psi)] k dk d\theta$$

$$P^*(X, Y, f) = \int_{-\pi}^{\pi} \int_0^{\infty} S(K, \theta, f) \exp[i2\pi K D \cos(\theta - \psi)] k dk d\theta \quad (7.13)$$

We have from Equation (3.2) that

$$S(k, \theta, f_0) = S(k, \theta - \pi, -f_0)$$

If we think in terms of  $f_0 > 0$

$$S'(k, \theta, f_0) = 2 S(k, \theta, f_0) \quad (7.14)$$

We are assuming that the wave number relation of Equation (3.1) holds. Thus Figure 3 is applicable, and we can write the one-sided spectral density as

$$S'(k, \theta, f_0) = 2 a(\theta, f_0) \delta(k - k_0)$$

$$\text{WHERE } \delta(k - k_0) = \begin{cases} 1 & k = k_0 \\ 0 & k \neq k_0 \end{cases}$$

This allows us to write,  $-\infty < f_0 < +\infty$ ,

$$P^*(x, y, f_0) = \int_{-\pi}^{\pi} \int_0^{\infty} a(\theta, f_0) \delta(k - k_0) \exp[i 2\pi k D \cos(\theta - \psi)] k dk d\theta$$

$$P^*(x, y, f_0) = \int_{-\pi}^{\pi} a(\theta, f_0) \exp[i 2\pi k_0 D \cos(\theta - \psi)] k_0 d\theta \quad (7.15)$$

We have reduced the problem to finding  $[a(\theta, f_0 \cdot k_0)]$ .

From Equation (7.15) we see that

$$P^*(0, 0, f) = P(f) = \int_{-\pi}^{\pi} a(\theta, f_0) k_0 d\theta$$

where  $P(f_0)$  is the power spectral density of frequency  $f_0$ . For better comparison of cases where  $P(f_1) = P(f_0)$ ,  $|f_1| \neq |f_0|$ , it is convenient to express  $a(\theta, f_0)$  in a normalized form

$$A(\theta, f_0) = a(\theta, f_0) k_0$$

where we get

$$P(f) = \int_{-\pi}^{\pi} A(\theta, f) d\theta \quad (7.16)$$

Thus if the energy distribution as a function of direction is the same for  $P(f_1) = P(f_0)$  then we also get

$$A(\theta, f_1) = A(\theta, f_0).$$

Consider now (assuming  $A(\theta, f)$  can be so expressed) a Fourier series expansion of  $A(\theta, f)$  for fixed  $f$ . Clearly it is periodic in  $\theta$  with period  $2\pi$ . Thus for any given  $f = f_0$  we can write  $A(\theta, f)$  as

$$A(\theta) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos n\theta + b_n \sin n\theta] \quad (7.17)$$

Substituting this expansion into Equation (7.15) we get

$$\begin{aligned} P^*(X, Y, f) &= \frac{a_0}{2} \int_{-\pi}^{\pi} \exp i 2\pi K D \cos(\theta - \psi) d\theta + \sum_{n=1}^{\infty} \left[ a_n \int_{-\pi}^{\pi} \cos n\theta \right. \\ &\quad \left. \exp i 2\pi K D \cos(\theta - \psi) d\theta + b_n \int_{-\pi}^{\pi} \sin n\theta \exp i 2\pi K D \cos(\theta - \psi) d\theta \right] \\ \text{or } P^*(X, Y, f) &= \left[ \frac{a_0}{2} \int_{-\pi}^{\pi} \cos(2\pi K D \cos(\theta - \psi)) d\theta + \sum_{n=1}^{\infty} \left( a_n \int_{-\pi}^{\pi} \cos n\theta \cos(2\pi K D \right. \right. \\ &\quad \left. \left. \cos(\theta - \psi)) d\theta + b_n \int_{-\pi}^{\pi} \sin n\theta \cos(2\pi K D \cos(\theta - \psi)) d\theta \right) \right] \\ &\quad + j \left[ \frac{a_0}{2} \int_{-\pi}^{\pi} \sin(2\pi K D \cos(\theta - \psi)) d\theta + \right. \\ &\quad \left. + \sum_{n=1}^{\infty} \left( a_n \int_{-\pi}^{\pi} \cos n\theta \sin(2\pi K D \cos(\theta - \psi)) d\theta + \right. \right. \\ &\quad \left. \left. b_n \int_{-\pi}^{\pi} \sin n\theta \sin(2\pi K D \cos(\theta - \psi)) d\theta \right) \right] \quad (7.18) \end{aligned}$$



Thus we can express  $P^*(X,Y,f)$  as complex infinite series with unknown coefficients  $a_0, a_1, a_2, \dots$  and  $b_1, b_2, \dots$  and constants defined by the integrals (let  $Z = 2\pi KD$ ;  $n = 0, 1, 2, \dots$ ) of the form

$$\int_{-\pi}^{\pi} \cos n\theta \cos(z \cos(\theta - \psi)) d\theta \quad (7.19)$$

$$\int_{-\pi}^{\pi} \sin n\theta \cos(z \cos(\theta - \psi)) d\theta \quad (7.20)$$

$$\int_{-\pi}^{\pi} \cos n\theta \sin(z \cos(\theta - \psi)) d\theta \quad (7.21)$$

and

$$\int_{-\pi}^{\pi} \sin n\theta \sin(z \cos(\theta - \psi)) d\theta \quad (7.22)$$

Consider Equation (7.19) where  $\phi = (\theta - \psi)$  and  $d\phi = d\theta$ ,  $\psi$  being a constant. We then have on changing variables

$$\begin{aligned} & \int_{-\pi-\psi}^{\pi-\psi} \cos(n\phi + n\psi) \cos(z \cos \phi) d\phi \\ &= \cos n\psi \int_{-\pi-\psi}^{\pi-\psi} \cos n\phi \cos(z \cos \phi) d\phi \\ & \quad - \sin n\psi \int_{-\pi-\psi}^{\pi-\psi} \sin n\phi \cos(z \cos \phi) d\phi \end{aligned} \quad (7.23)$$

Since the integrands in Equation (7.23) are both of period  $2\pi$  and the interval  $[-\pi-\psi, \pi-\psi]$  is of length  $2\pi$  we can write the equivalent of Equation (7.23) as

$$\begin{aligned} & \cos n\psi \int_{-\pi}^{\pi} \cos n\phi \cos(z \cos \phi) d\phi \\ & - \sin n\psi \int_{-\pi}^{\pi} \sin n\phi \cos(z \cos \phi) d\phi \end{aligned} \quad (7.24)$$

From Ryzhik and Gradshteyn (1965 - page 402) and noting that the second integrand is odd we get Equation (7.23) equivalent to

$$\cos n\psi \left[ 2\pi \cos\left(\frac{n\pi}{2}\right) J_n(\bar{x}) \right] \quad (7.25)$$

where  $J_n(Z)$  is the Bessel function of the first kind. Employing a similar procedure for Equations (7.20), (7.21), and (7.22) we get

$$\begin{aligned} P^*(X, Y, f) = & \frac{Q_0}{2} \left[ 2\pi J_0(2\pi KD) \right] + \\ & \sum_{n=1}^{\infty} \left[ a_n \cos n\psi 2\pi \cos\left(\frac{n\pi}{2}\right) J_n(2\pi KD) + b_n \sin n\psi 2\pi \right. \\ & \quad \left. \cos\left(\frac{n\pi}{2}\right) J_n(2\pi KD) \right] \\ & + j \sum_{n=1}^{\infty} \left[ a_n \cos n\psi 2\pi \sin\left(\frac{n\pi}{2}\right) J_n(2\pi KD) \right. \\ & \quad \left. + b_n \sin n\psi 2\pi \sin\left(\frac{n\pi}{2}\right) J_n(2\pi KD) \right] \end{aligned} \quad (7.26)$$

Now 
$$\cos\left(\frac{n\pi}{2}\right) = \begin{cases} 0 & n \text{ odd} \\ (-1)^{n/2} & n \text{ even} \end{cases}$$

and 
$$\sin\left(\frac{n\pi}{2}\right) = \begin{cases} 0 & n \text{ even} \\ (-1)^{(n-1)/2} & n \text{ odd} \end{cases}$$

Thus we get 
$$\begin{aligned} P^*(X, Y, f) = & \frac{Q_0}{2} \left[ 2\pi J_0(2\pi KD) \right] \\ & + \sum_{n=2,4,6,\dots}^{\infty} \left[ 2\pi J_n(2\pi KD) (-1)^{n/2} (a_n \cos n\psi + b_n \sin n\psi) \right] \\ & + j \sum_{n=1,3,5,\dots}^{\infty} \left[ 2\pi J_n(2\pi KD) (-1)^{(n-1)/2} (a_n \cos n\psi + b_n \sin n\psi) \right] \end{aligned} \quad (7.27)$$

From a spectral matrix of the form in Equation (4.13),  $M = N(N-1) + 1$  different equations can be set up using Equation (7.27). This allows us to get a system of equations for any  $m$  of the unknown coefficients  $a_0, a_1, a_2, \dots; b_1, b_2, b_3, \dots$  while assuming the rest of the coefficients are negligible. We can then solve for the  $m$  desired coefficient values. This has not worked well in practice for two reasons. The inverse of the matrix of constants obtained is sparse and often ill-conditioned. Further, if the wave energy is from a narrow beam width (30 degrees or less), the first 100 harmonics in the Fourier series expansion can be significant. There is perhaps a more efficient orthogonal set of functions than the sines and cosines of the standard Fourier expansion. Search for such an orthogonal set should prove fruitful. One might start with Walsh or Haar functions. See Hammond and Johnson (February 1960).

## 8. SUMMARY

It is believed that the least square method of using the information in a spectral matrix is the best method presently available. Examples of such analysis can be found in several of the papers in the bibliography. A collection of ocean-wave induced, bottom pressure directional spectra from these papers is given in Appendix A.

An iterative extension of the least square method can be found in an excellent paper by Munk et al (April 1963). Some details of this method are given in Appendix C along with an example result and a FORTRAN program for the method.

There is merit to using the coherency,

$$R_{ij}(f) = \frac{|P_{ij}(f)|}{(P_{ii} P_{jj})^{\frac{1}{2}}},$$

to form the weights  $b_{ij}$  in Equation (4.16). One idea being explored is

$$b_{ij} = \frac{R_{ij}}{1 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N R_{ij}} = \frac{R_{ij}}{R}.$$

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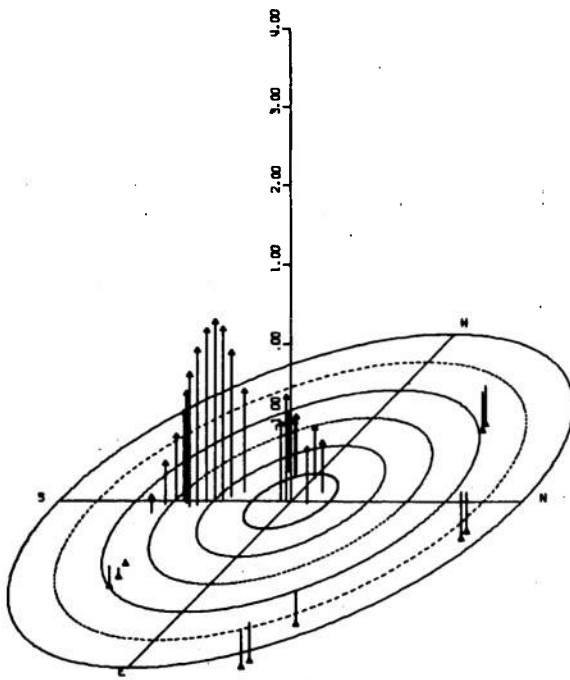
Scripps Institute of Oceanography Bulletin, *Spectra of Low-Frequency Ocean Waves*, by W. H. Munk, F. E. Snodgrass, and J. J. Tucker, v. 7, No. 4, pp. 283-362, 1959.

## APPENDIX A

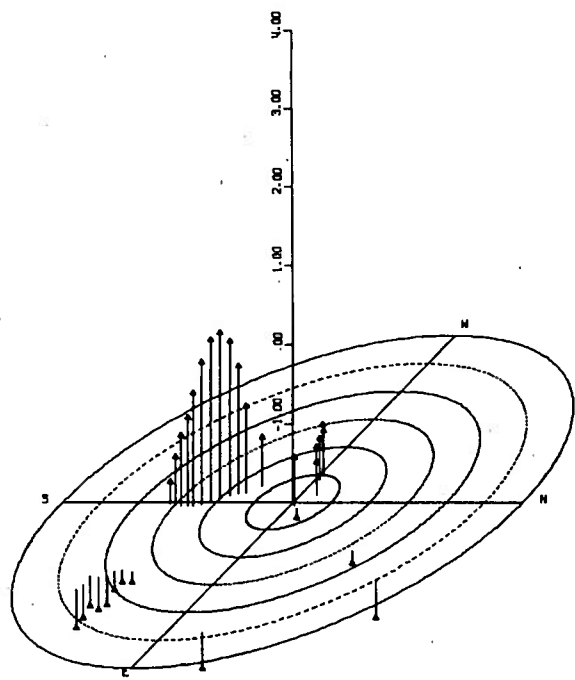
### A COLLECTION OF DIRECTIONAL OCEAN WAVE BOTTOM PRESSURE POWER SPECTRA

This appendix is a collection of the results of a least square, directional, single-wave train analysis of the cross power spectral matrix resulting from the analysis of ocean bottom pressure data. The data were collected at Stages I and II offshore from Panama City, Florida, during 1965. The data collection system and the estimation of the cross power spectral matrix associated with a set of data are described in Bennett, et al (June 1964). Augmented pentagonal arrays, containing six pressure transducers each, were located seaward of each of the stages. Stage I is 11 miles offshore in approximately 103 feet of water, and Stage II is 2 miles offshore in approximately 63 feet of water.

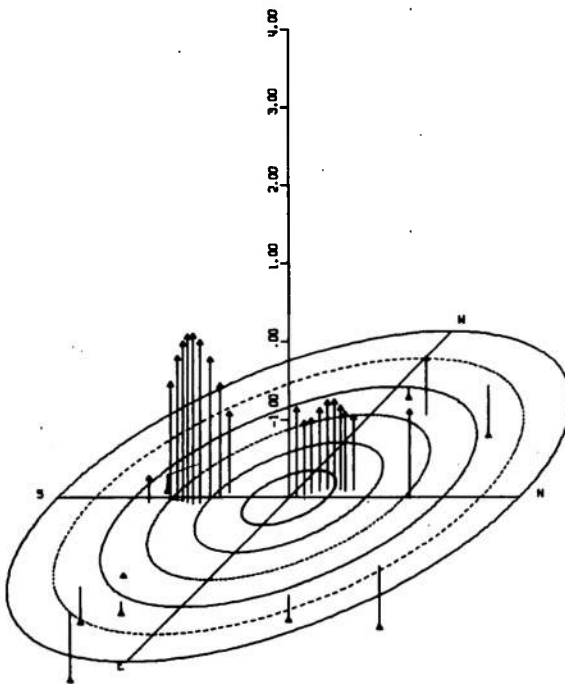
Certain parameter values are pertinent to the directional analyses presented: the number of data points in each pressure data set is  $N = 1800$ ; the sampling rate is once per second,  $\Delta t = 1$  second. On the cylindrical polar plots frequency is the radial variable and compass bearing the angular variable. The vertical axis is  $\log_{10}$  of power spectral density in inches<sup>2</sup>-seconds of water pressure. The frequency axis range is 0 to 0.3 Hz in 0.05 Hz increments. This is illustrated in Figure 7 of the report. In each plot title, the date, time, and location (stage) is indicated. The value WD is wind direction in compass degrees, and WS is wind speed in knots. Appendix B gives a listing of the FORTRAN II computer program used to produce the plots.



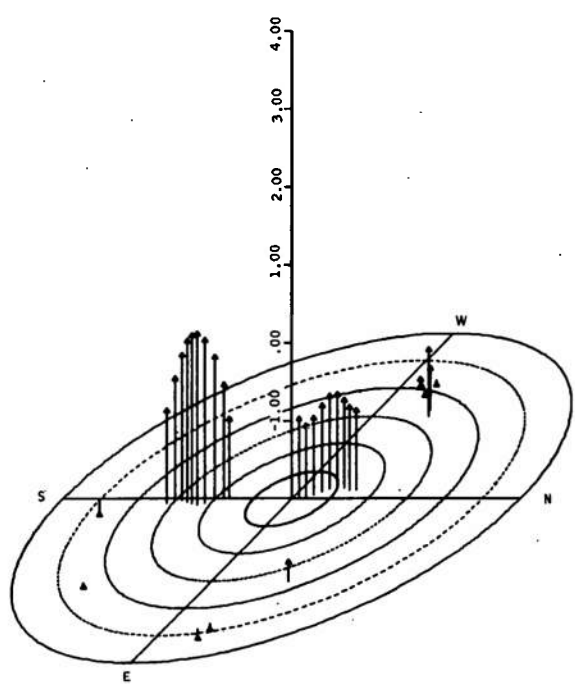
DATE06/01/65 TIME1159-1226 STAGE1 MO185



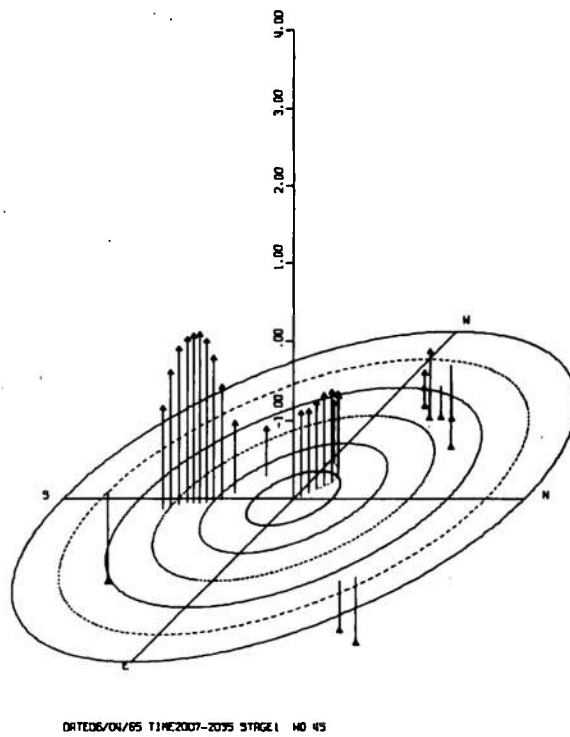
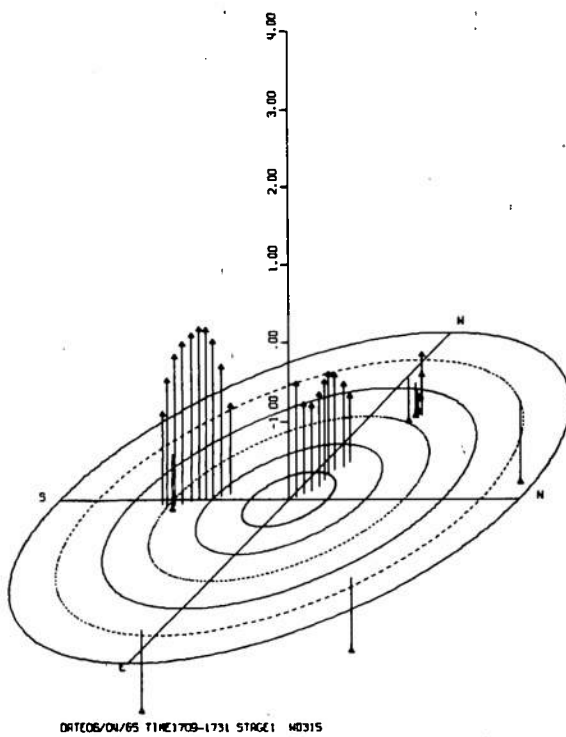
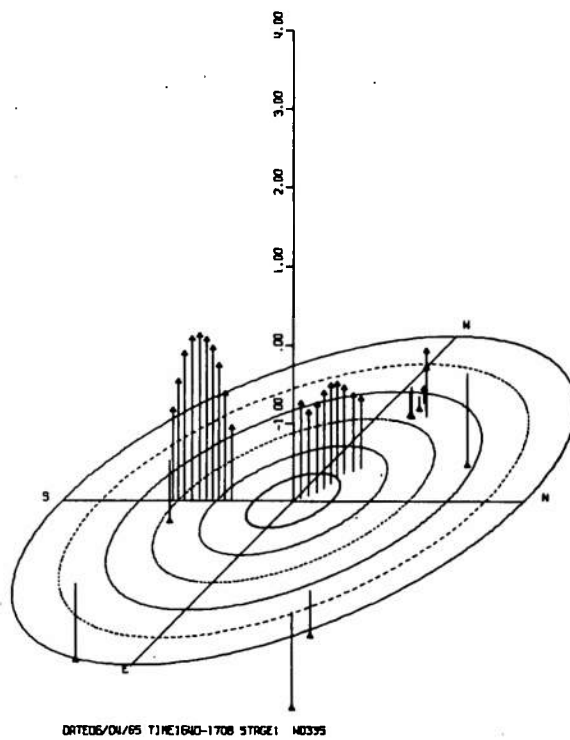
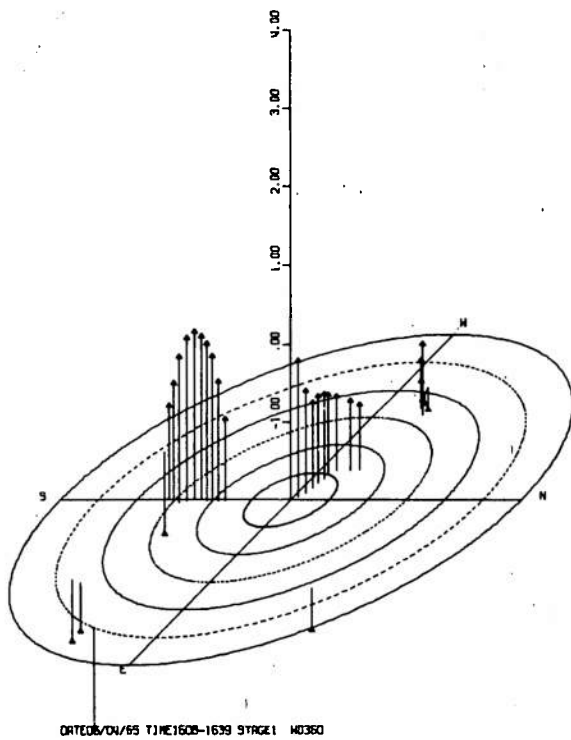
DATE06/01/65 TIME1227-1259 STAGE1 MO170



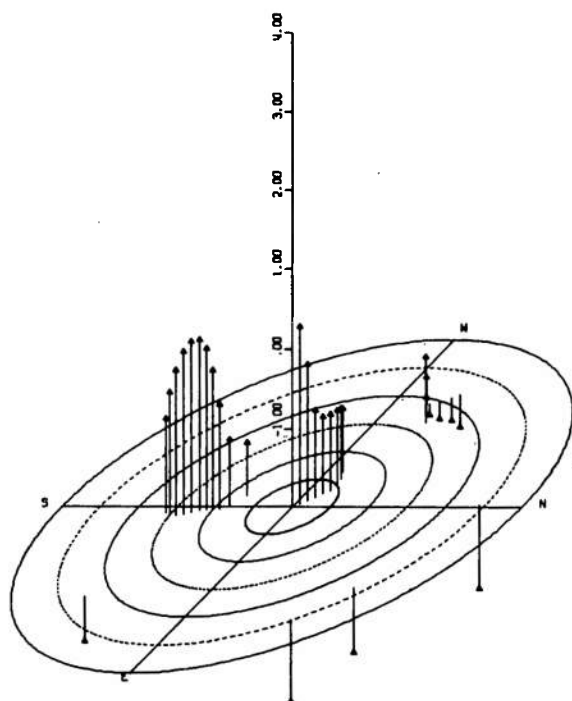
DATE06/01/65 TIME1415-1449 STAGE1 MO282



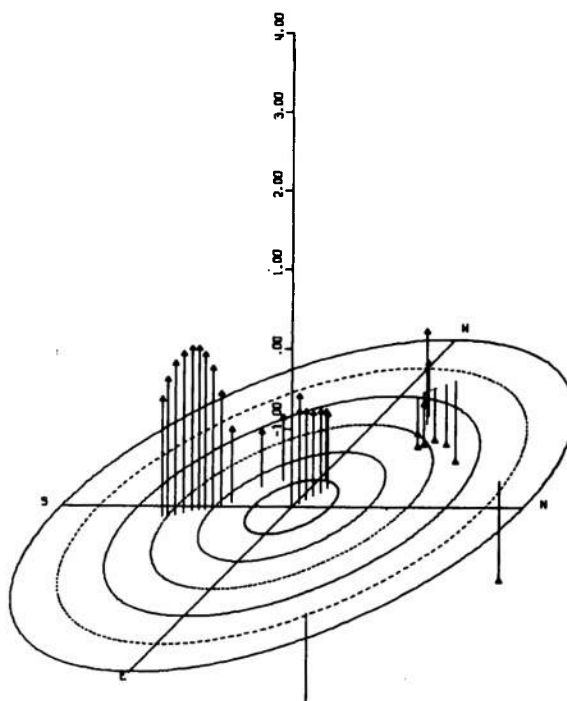
DATE06/04/65 TIME1418-1449 STAGE1 W0282



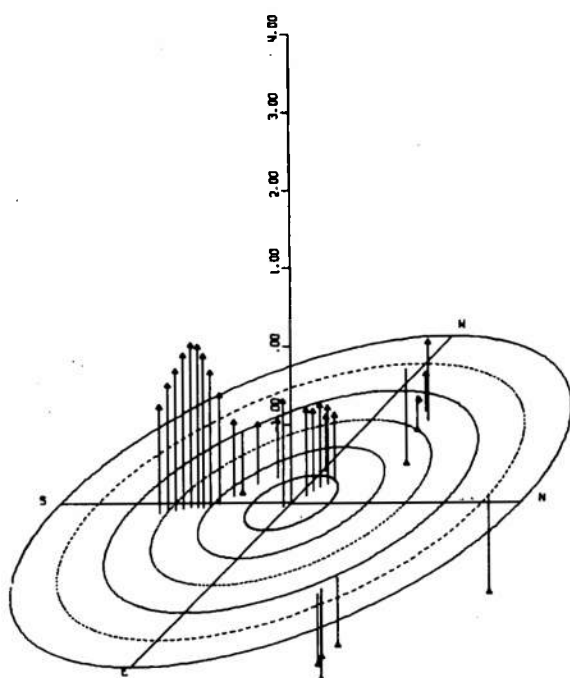




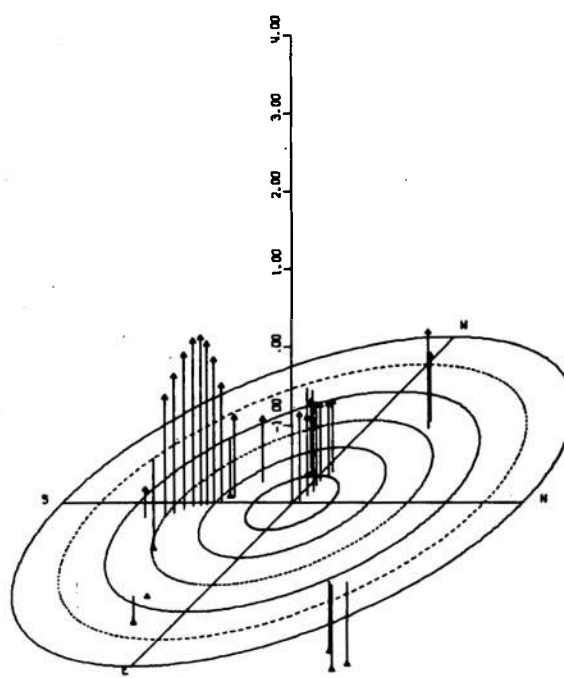
DATE06/04/65 TIME2105-2133 STAGE1 NO 00



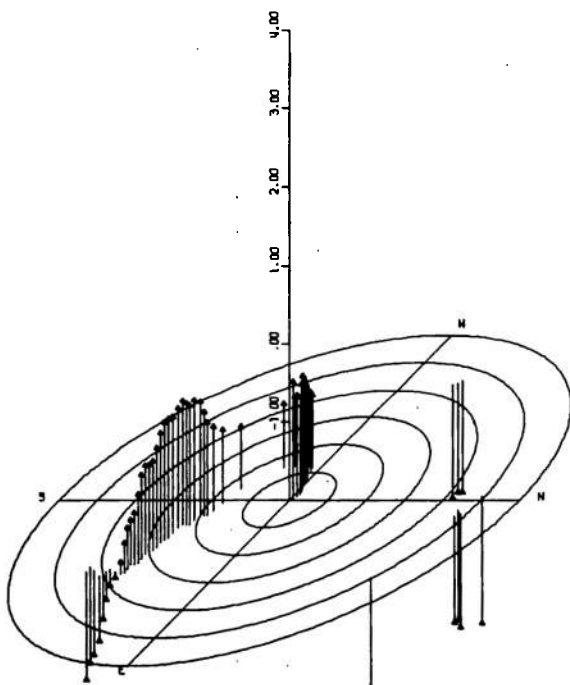
DATE06/05/65 TIME0003-0032 STAGE1 NO100



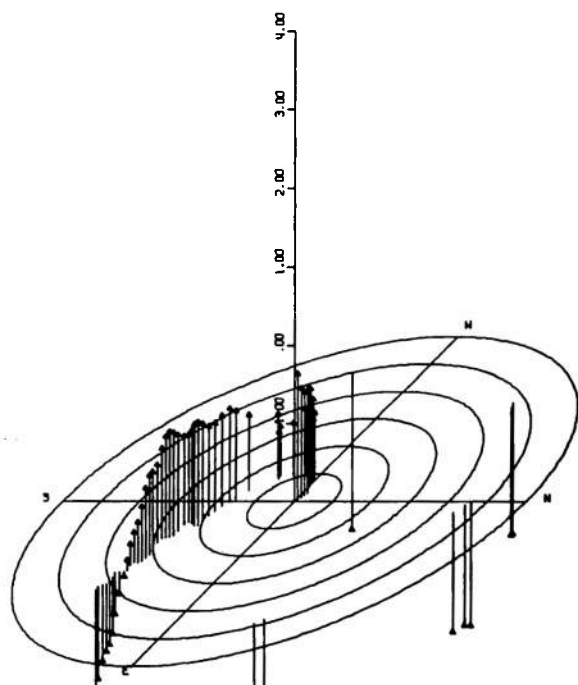
DATE06/05/65 TIME0033-0101 STAGE1 NO100



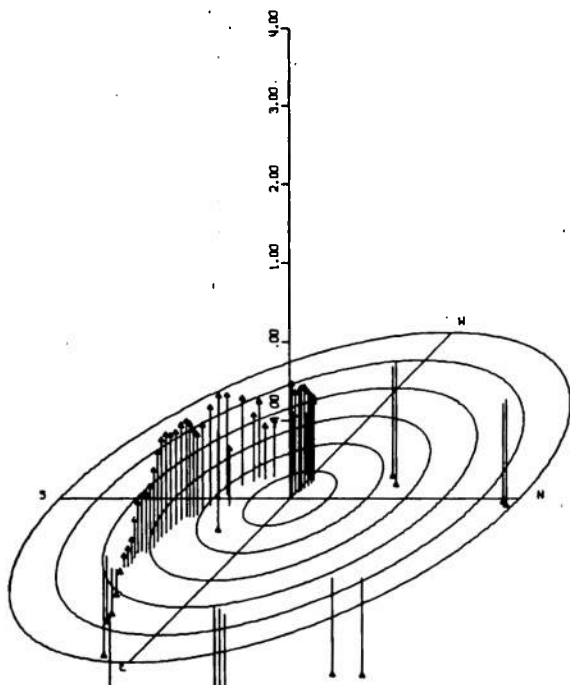
DATE06/05/65 TIME0102-0130 STAGE1 NO100



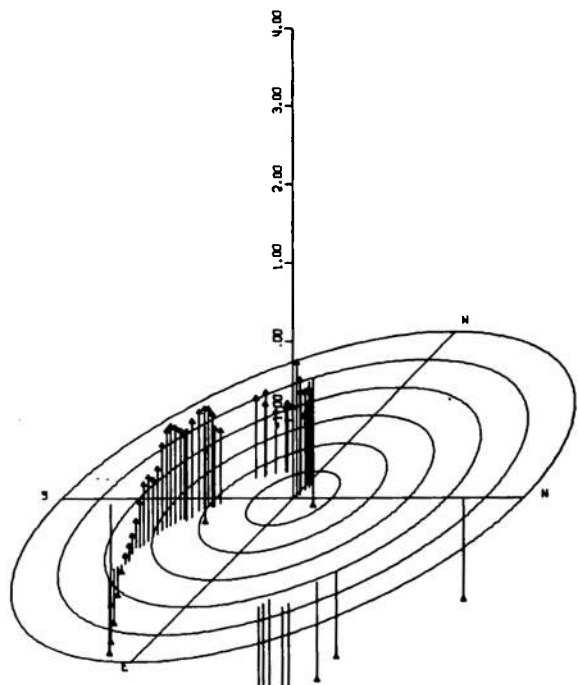
1701-1730 07SEP65 S1 H0073 H516 T32WF1R145-174 RUN 22



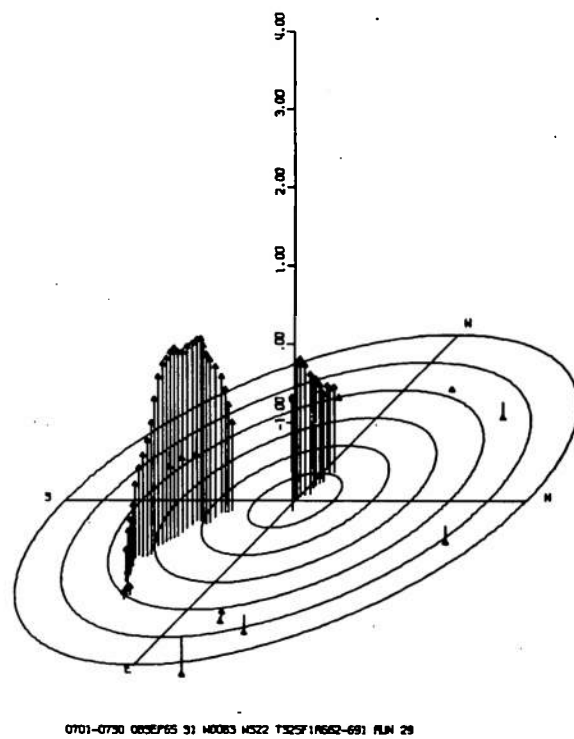
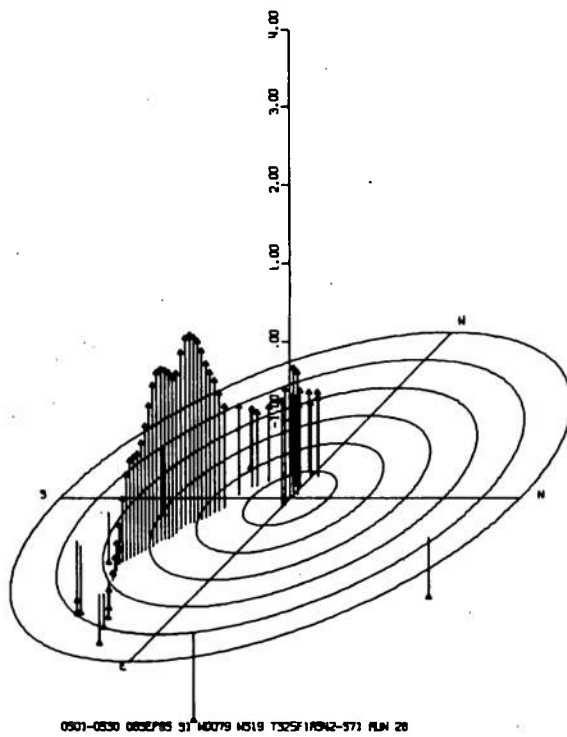
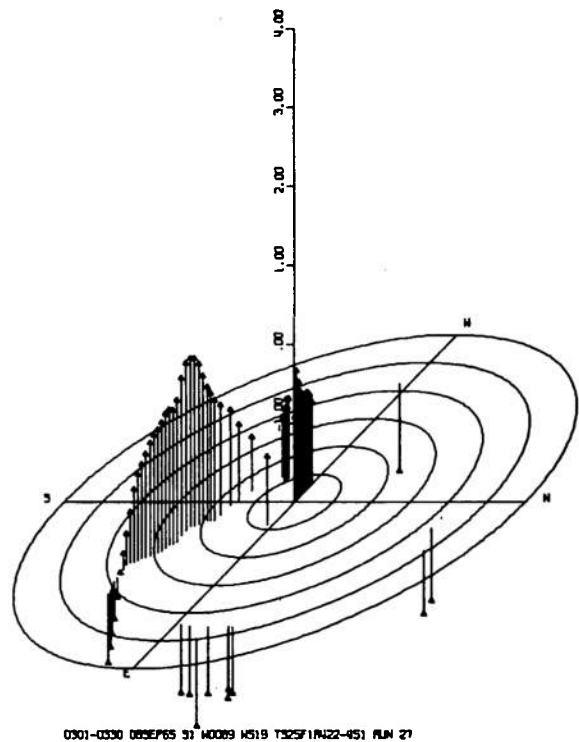
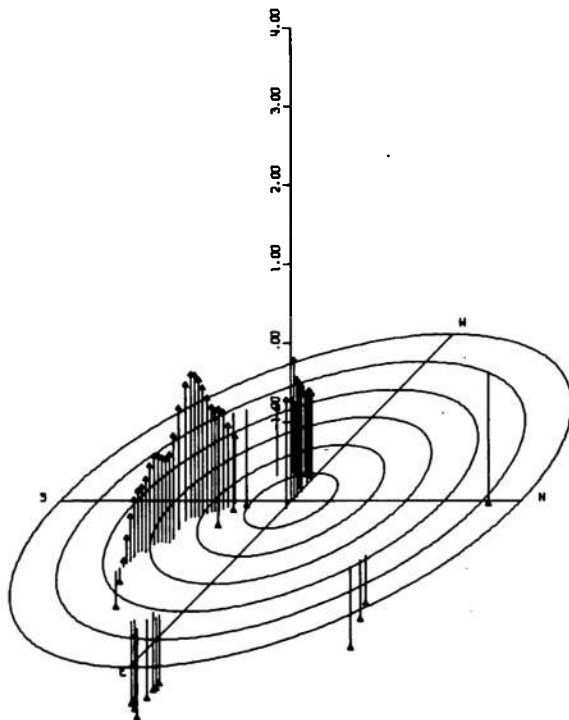
1901-1930 07SEP65 S1 H0060 H511 T32WF1R265-194 RUN 23

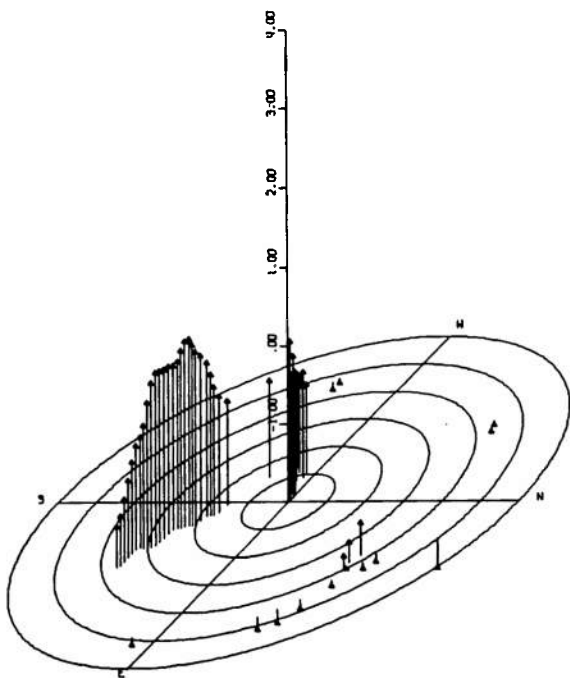


2101-2130 07SEP65 S1 H0073 H522 T32WF1R062-091 RUN 24

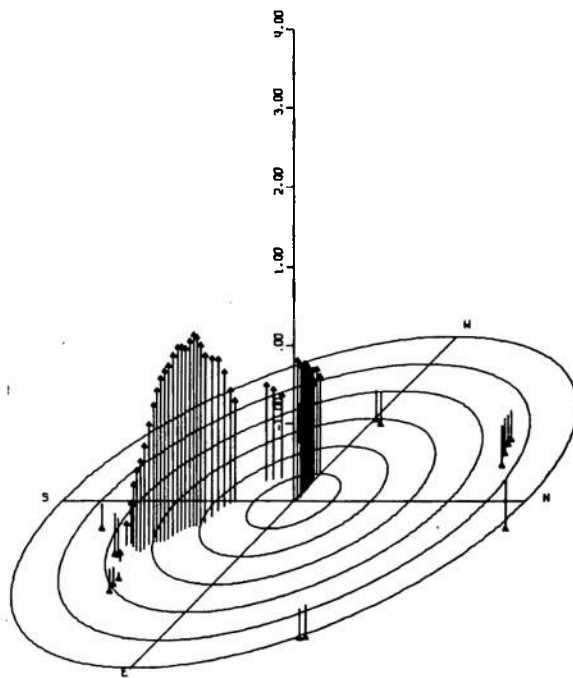


2301-2330 07SEP65 S1 H0062 H519 T32WF1R162-211 RUN 25

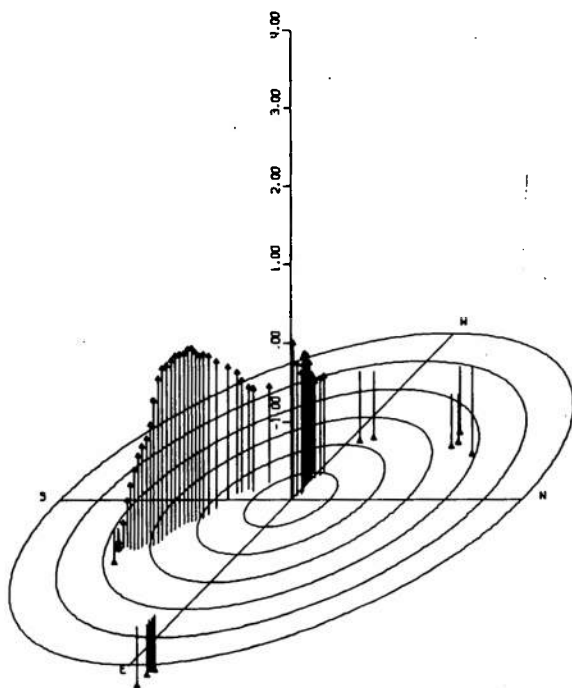




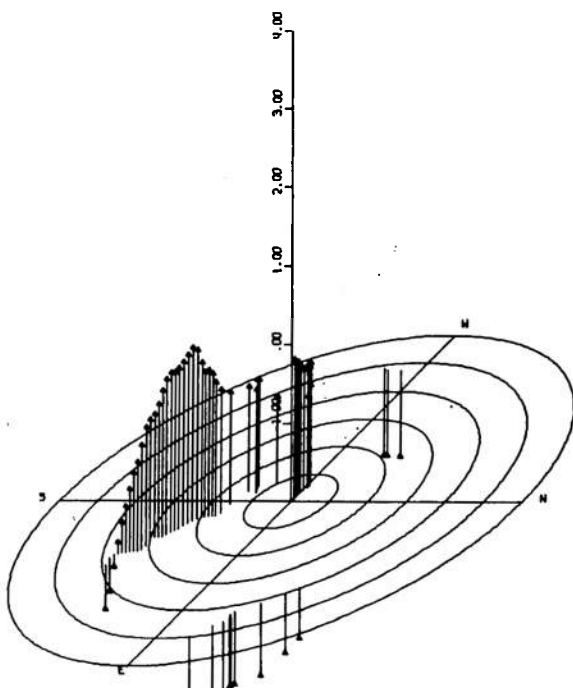
0901-0930 08SEP65 31 40077 4516 7326F1A094-093 RUN 30



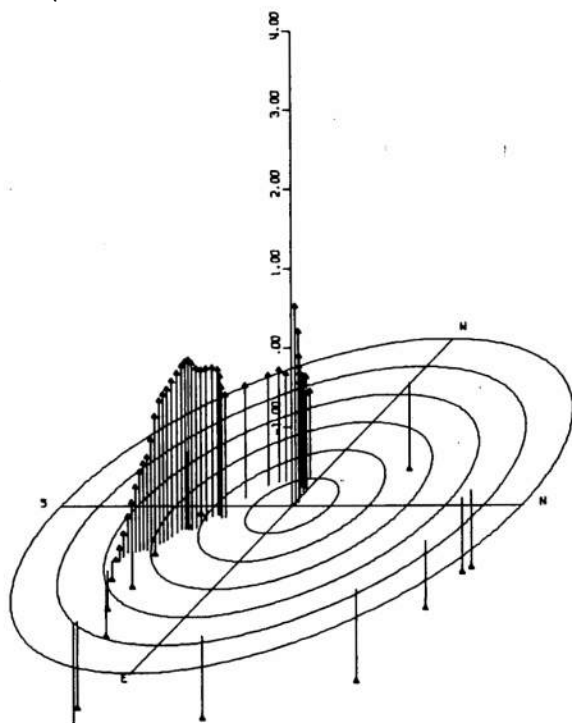
1101-1131 08SEP65 31 40141 4516 7326F1A104-213 RUN 31



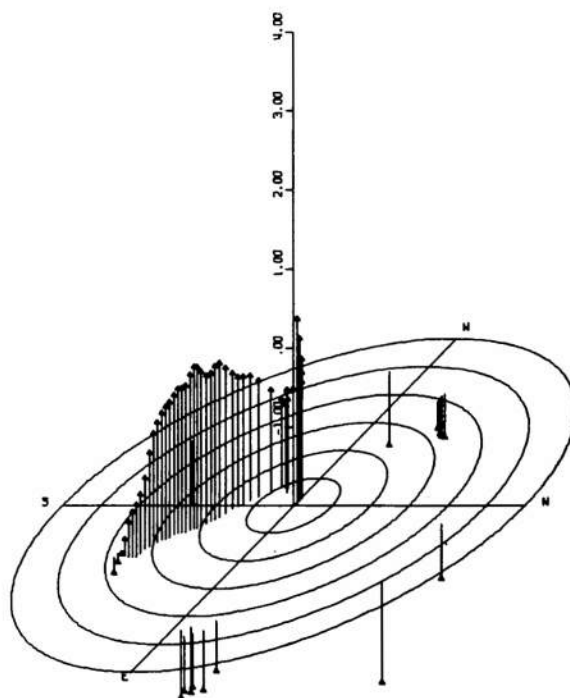
1301-1331 08SEP65 31 40055 4517 7326F1A304-333 RUN 32



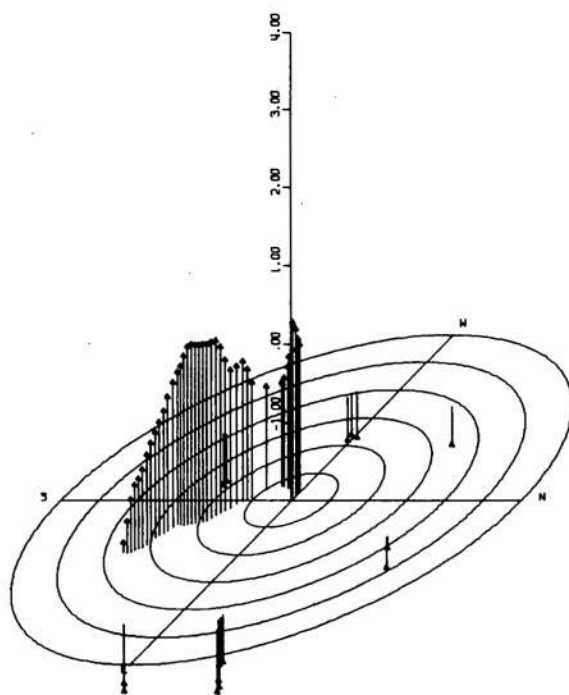
1501-1531 08SEP65 31 40070 4517 7326F1A424-453 RUN 33



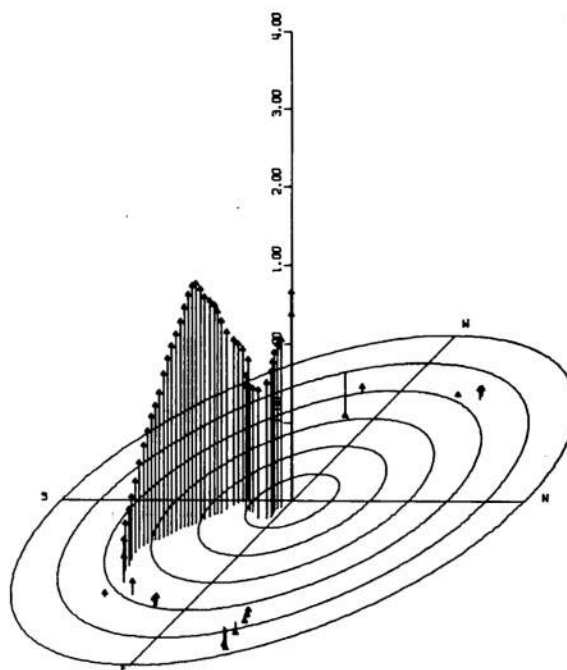
1701-1731 083E/65 51 M0072 M521 T326F1M944-573 RUN 34



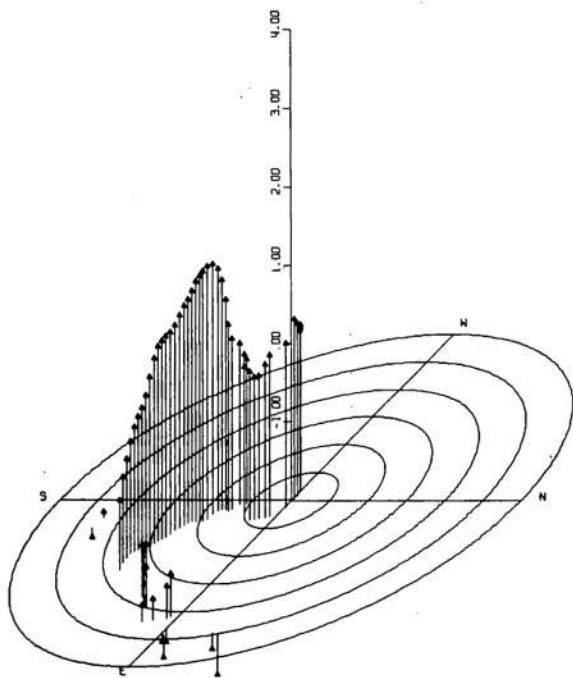
1901-1931 083E/65 51 M0071 M522 T326F1M684-693 RUN 35



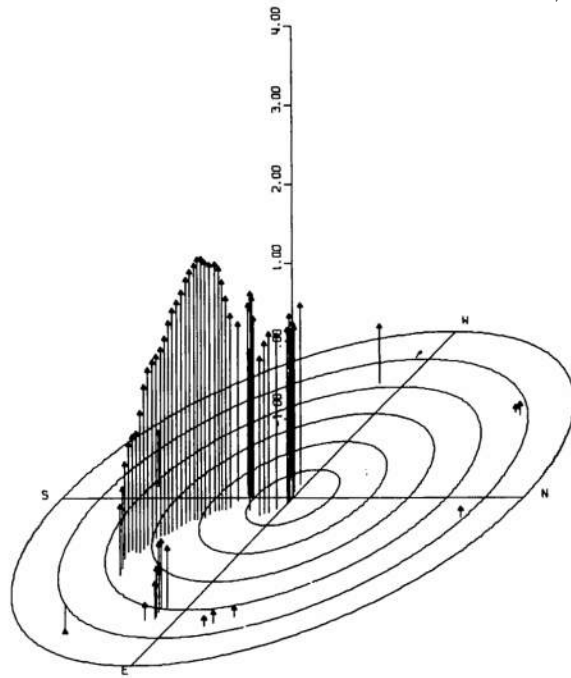
2101-2130 083E/65 51 M0074 M525 T327F2M042-071 RUN 36



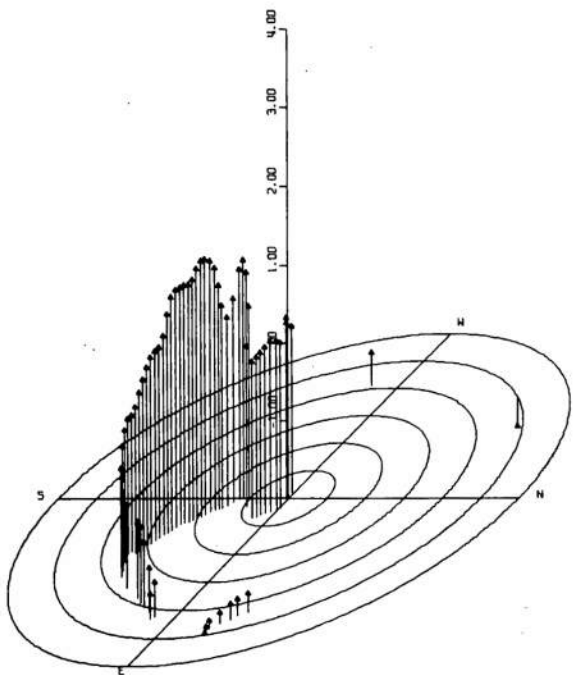
2301-2330 083E/65 51 M5083 M526 T327F2M162-191 RUN 37



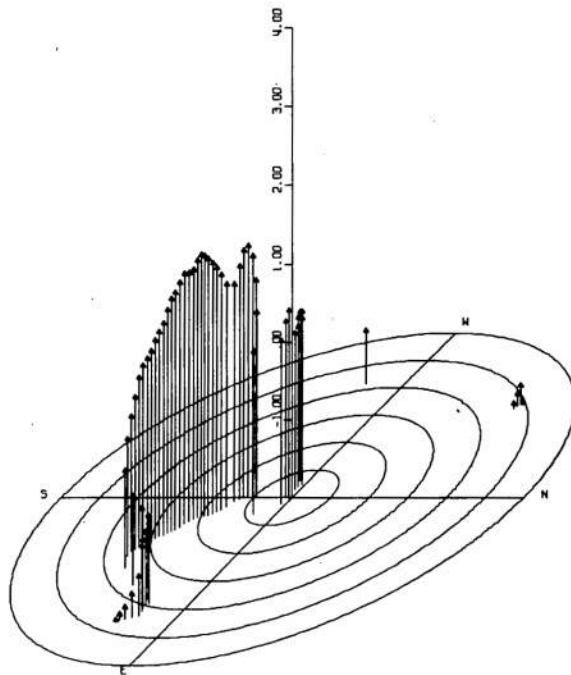
0101-0130 09SEP65 S1 W0081 W526 1327F2R262-311 RUN 38



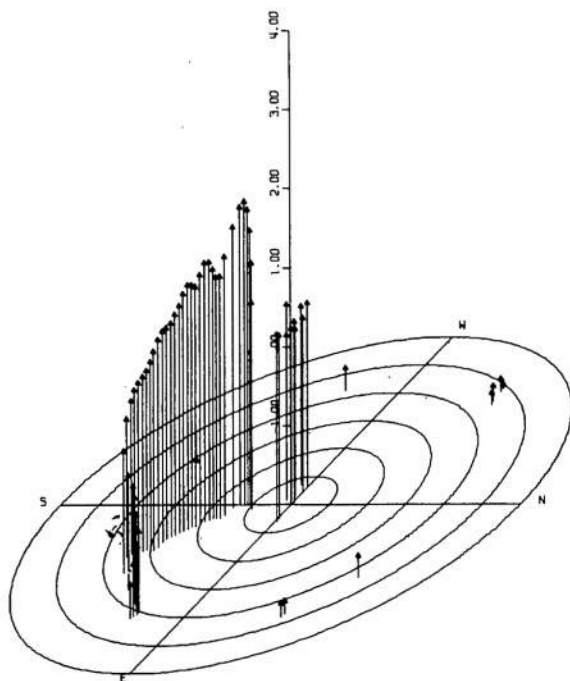
0201-0230 09SEP65 S1 W5085 W527 1327F2R342-371 RUN 39



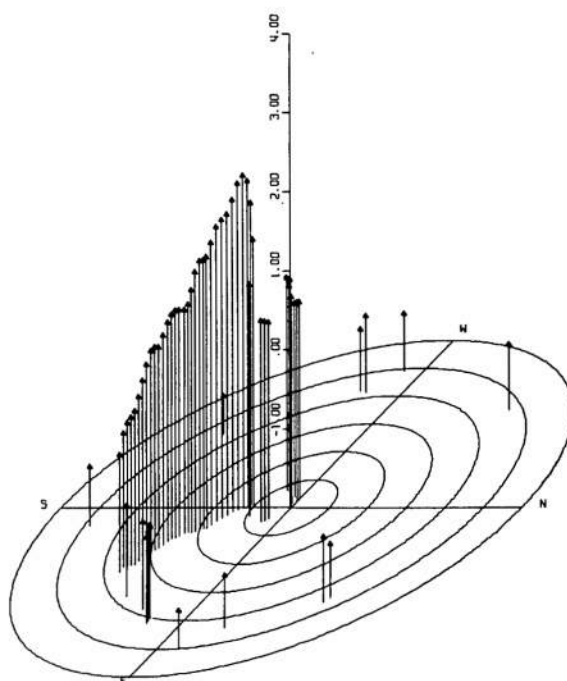
0301-0330 09SEP65 S1 W0080 W527 1327F2R402-431 RUN 40



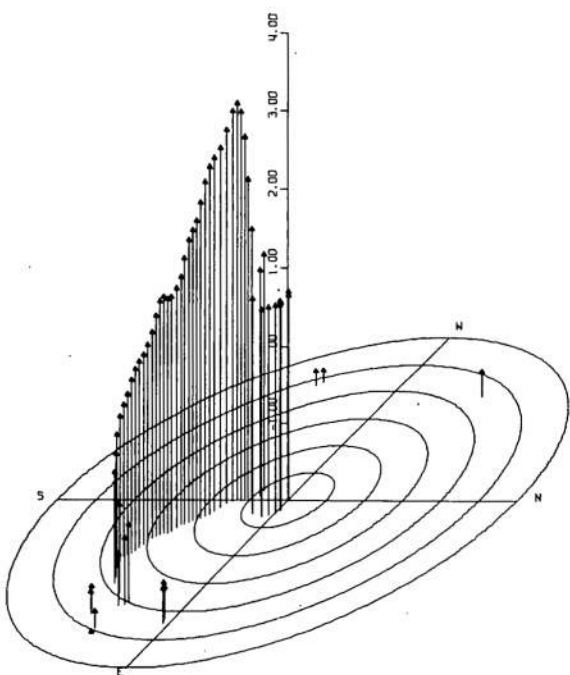
0401-0430 09SEP65 S1 W0082 W526 1327F2R462-491 RUN 41



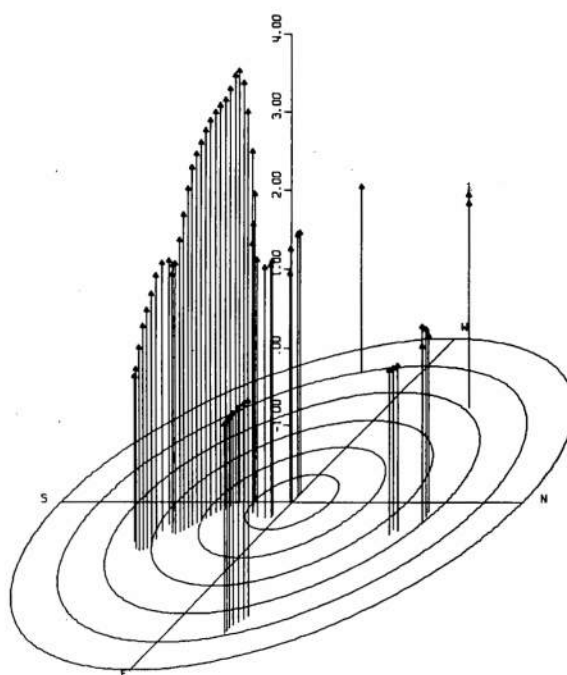
0501-0530 09SEP65 S1 W0085 W528 1327F27522-551 RUN 42



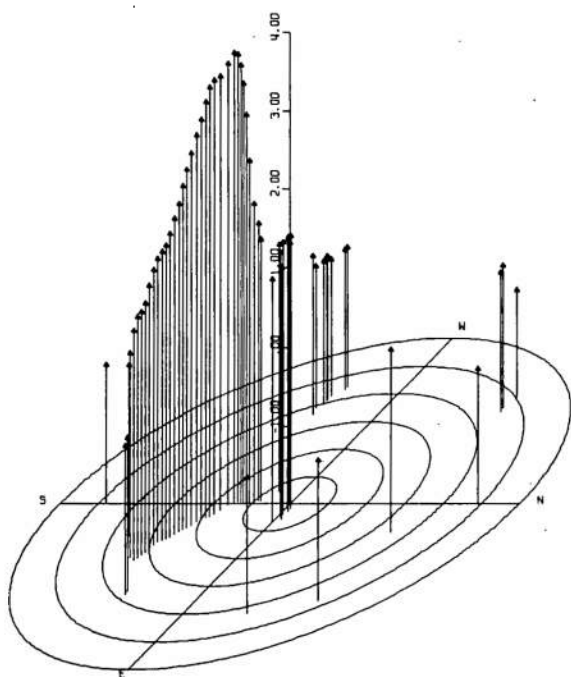
0601-0630 09SEP65 S1 W0088 W528 1327F27562-611 RUN 43



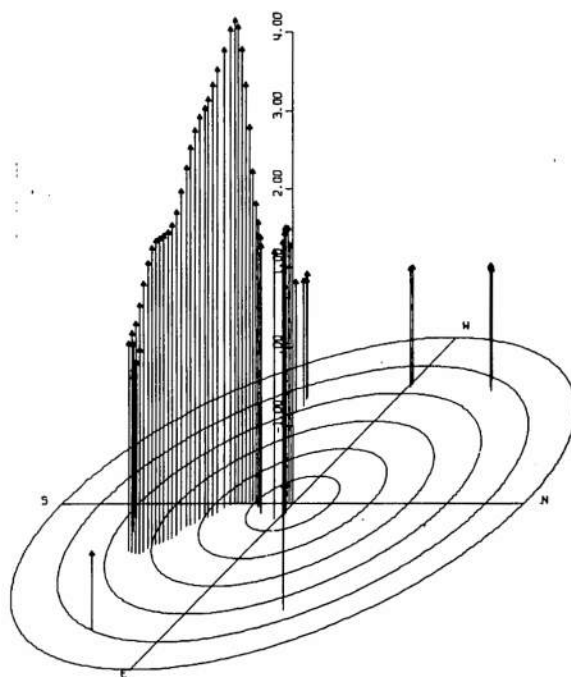
0701-0730 09SEP65 S1 W0092 W528 1327F28642-771 RUN 44



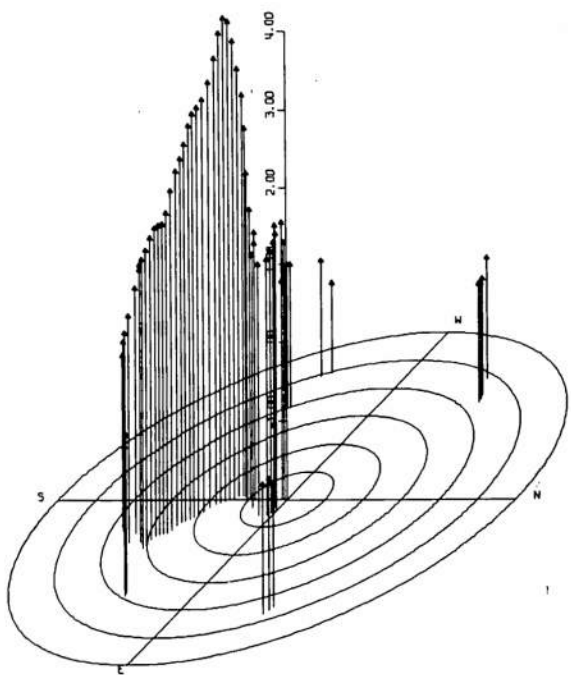
0801-0830 09SEP65 S1 W0103 W527 T083F1A003-032 RUN 45



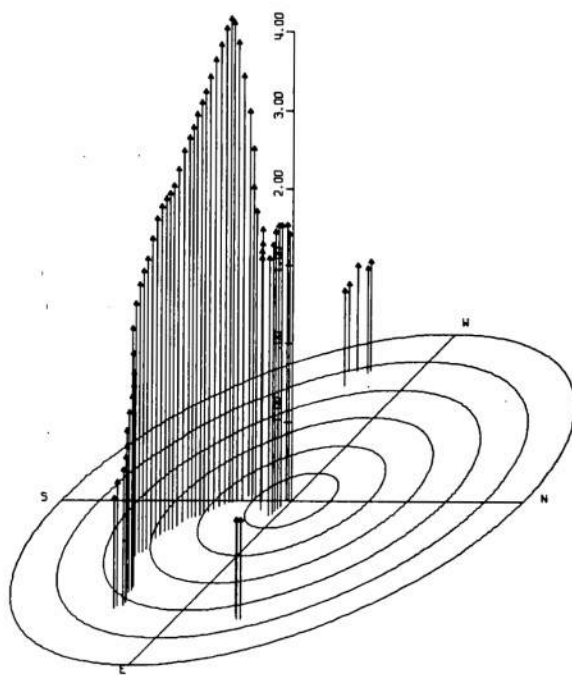
0901-0930 09SEP65 S1 W0117 W526 T083F1R063-092 RUN 46



1001-1030 09SEP65 S1 W0123 W533 T083F1R123-152 RUN 47

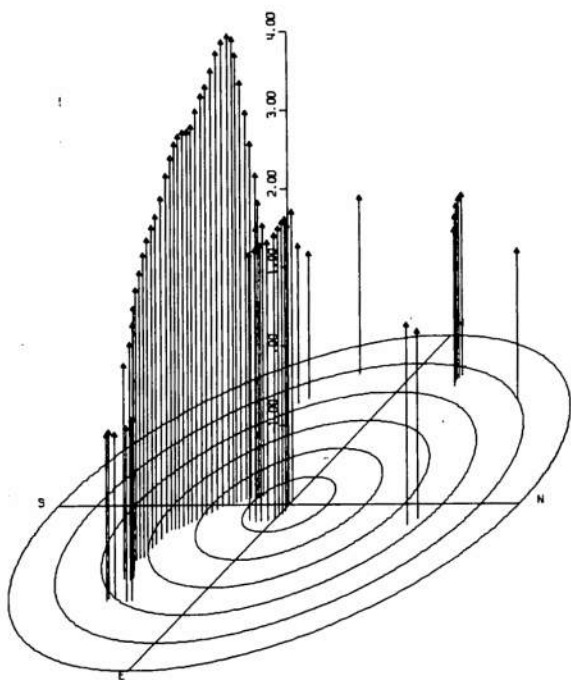


1101-1131 09SEP65 S1 W0125 W534 T083F1R183-212 RUN 48

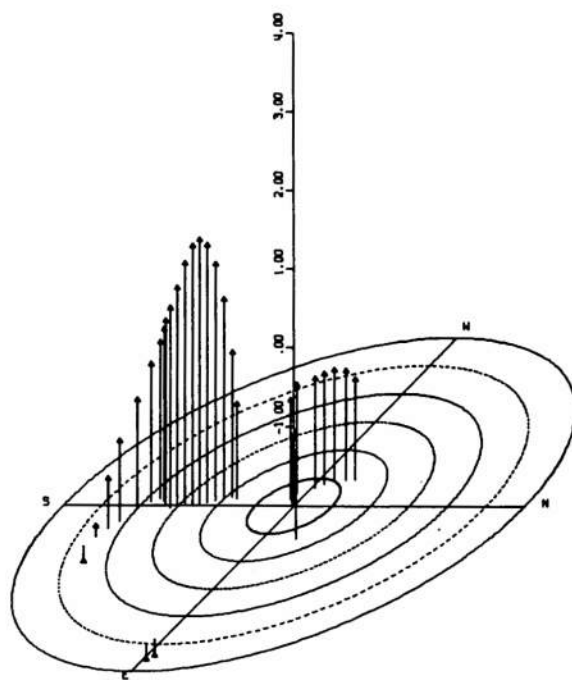


1201-1230 09SEP65 S1 W0130 W534 T083F1R243-272 RUN 49

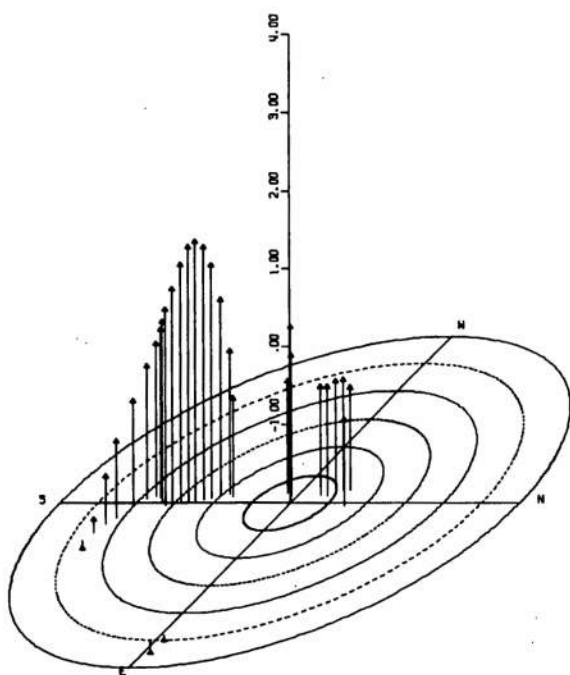




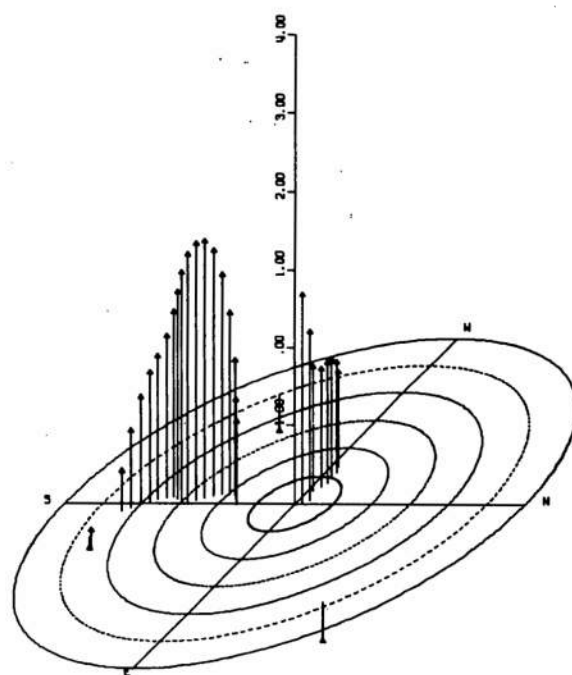
1310-1339 09SEP65 51 M0133 M535 T063F2/001-030 RUN 50



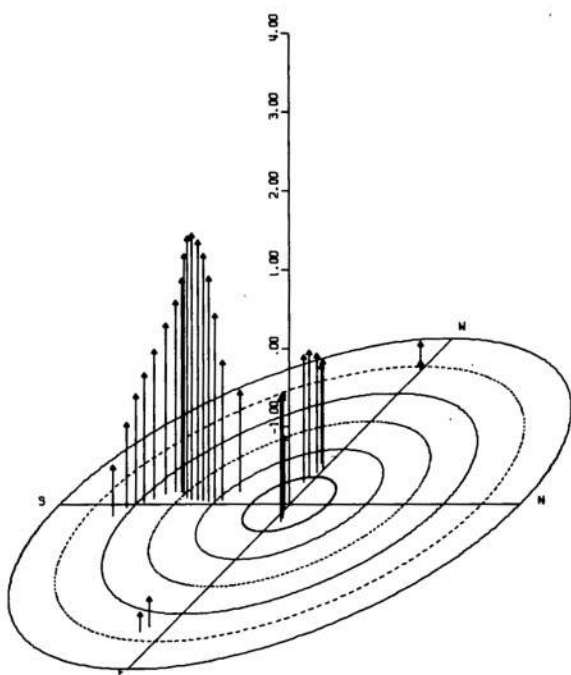
01005/04/65 TIME1200-1229 STRGE2 M0 02



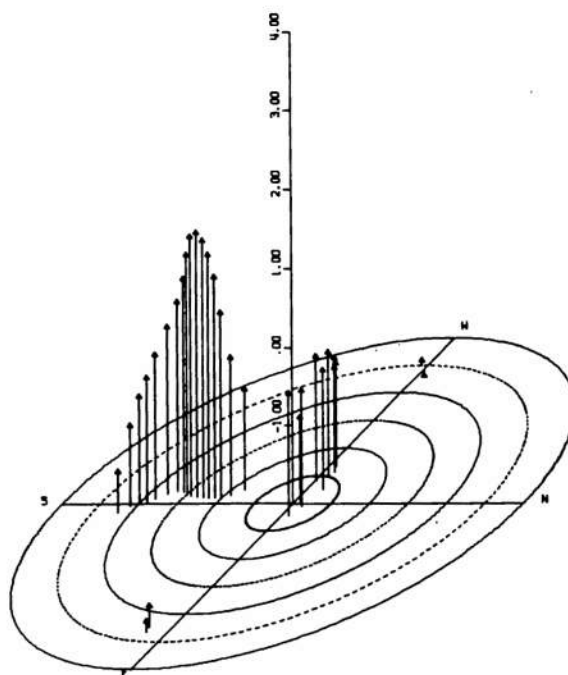
01005/04/65 TIME1200-1229 STRGE2 M0 02



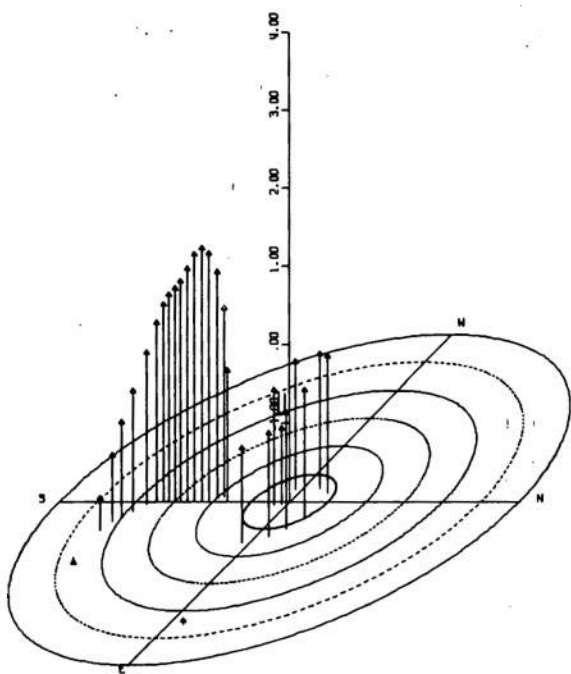
01005/04/65 TIME1301-1333 STRGE2 M0 05



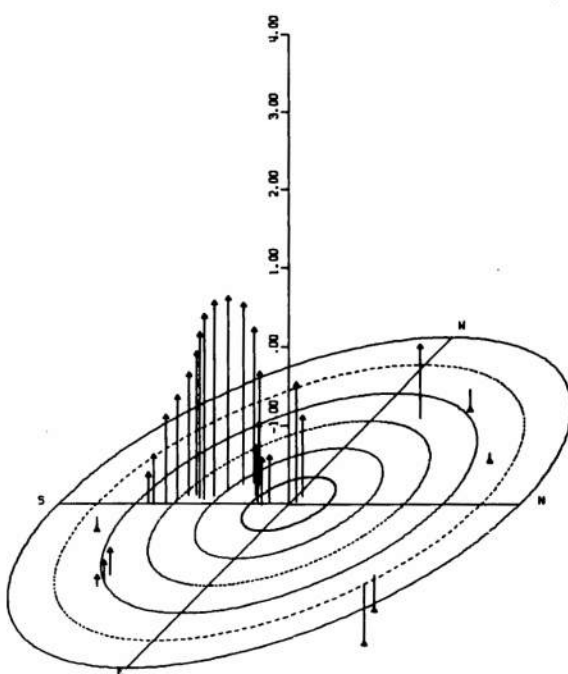
DATE05/04/65 TIME1401-1425 STAGE2 MD113



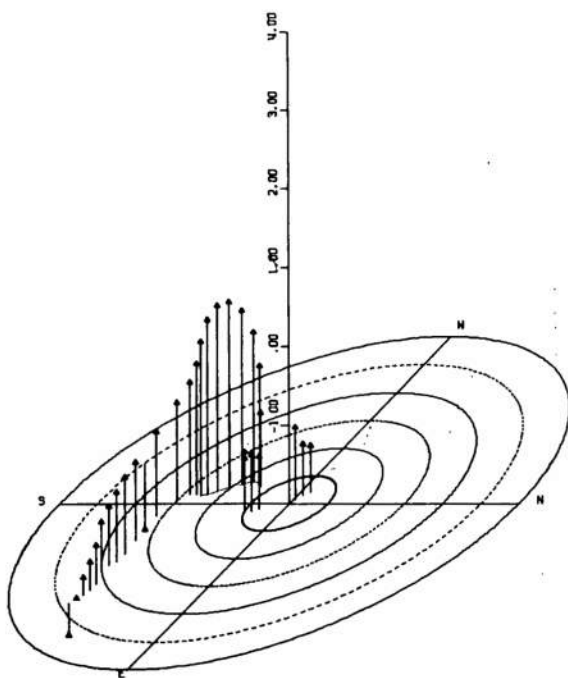
DATE05/04/65 TIME1401-1425 STAGE2 MD113



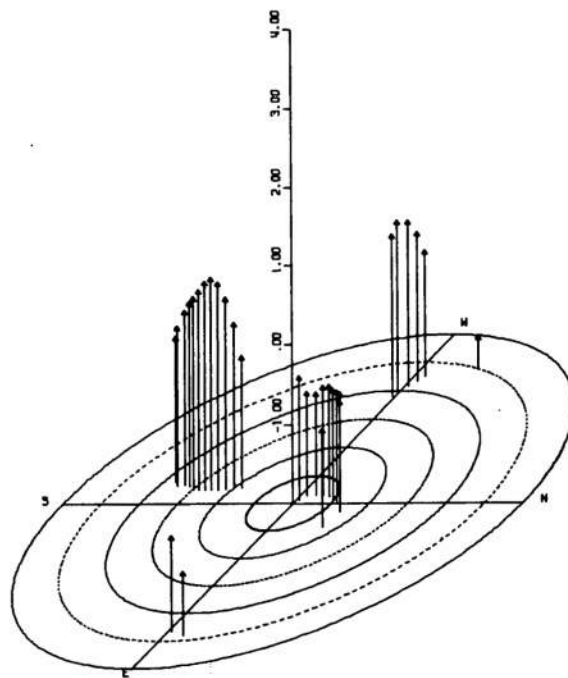
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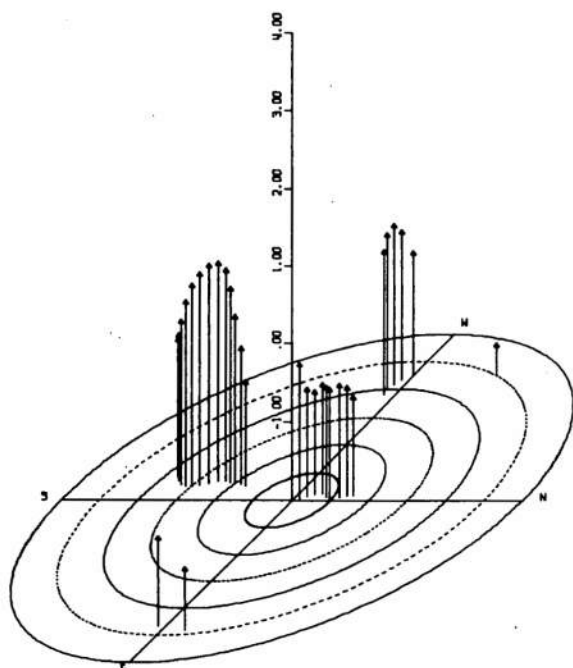
DATE06/01/65 TIME1154-1220 STAGE2 MD165



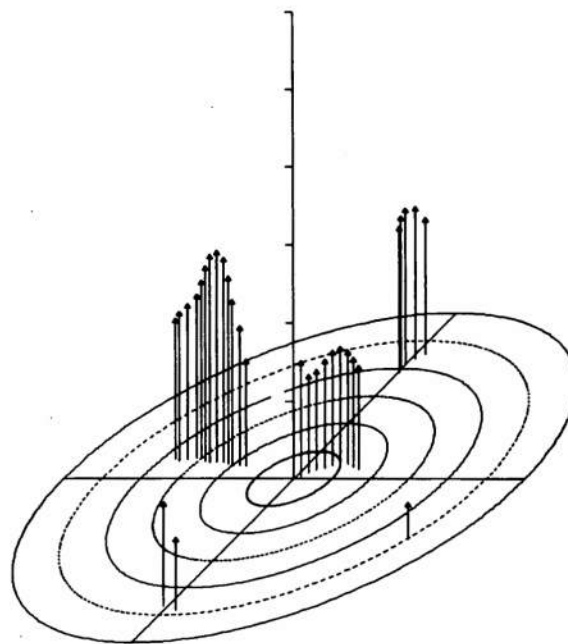
DATE06/01/65 TIME1220-1245 STAGE2 M0173



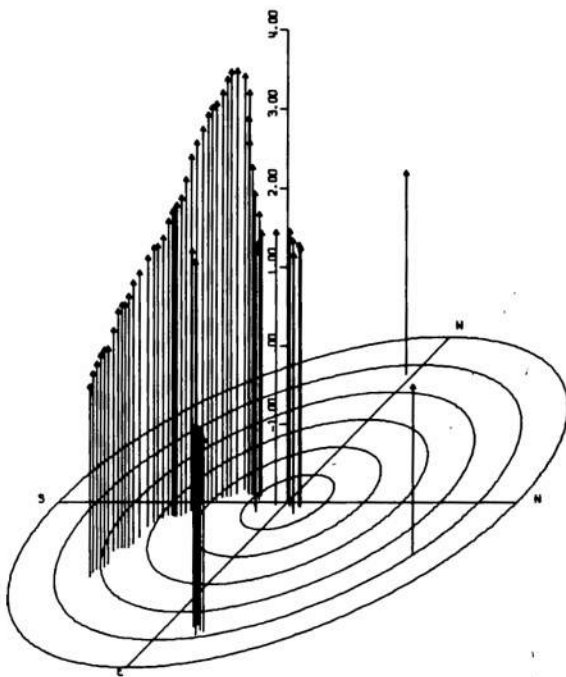
DATE06/04/65 TIME1049-1119 STAGE2 M0290



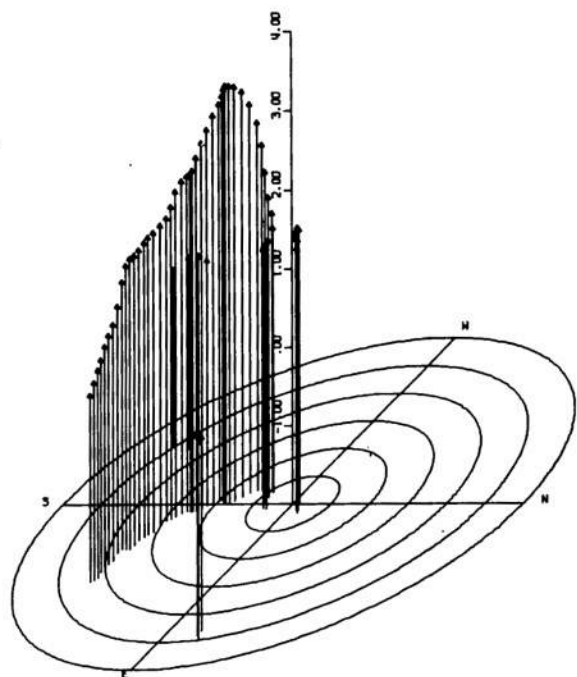
DATE06/04/65 TIME1200-1230 STAGE2 M0285



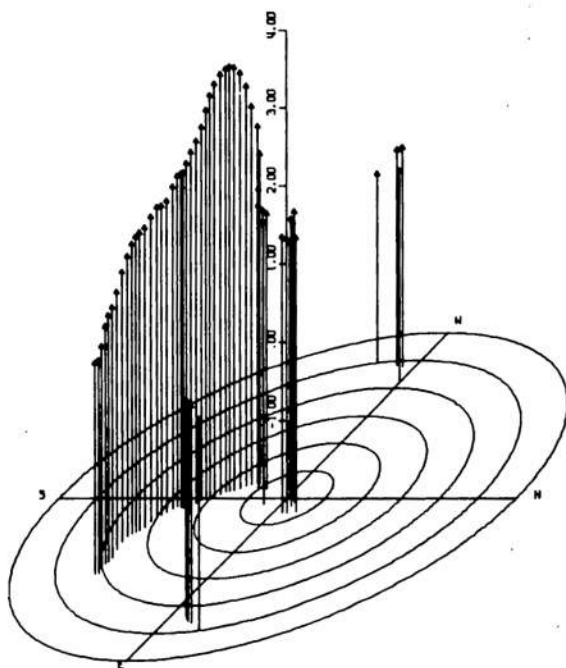
DATE06/04/65 TIME1300-1330 STAGE 2 W0280



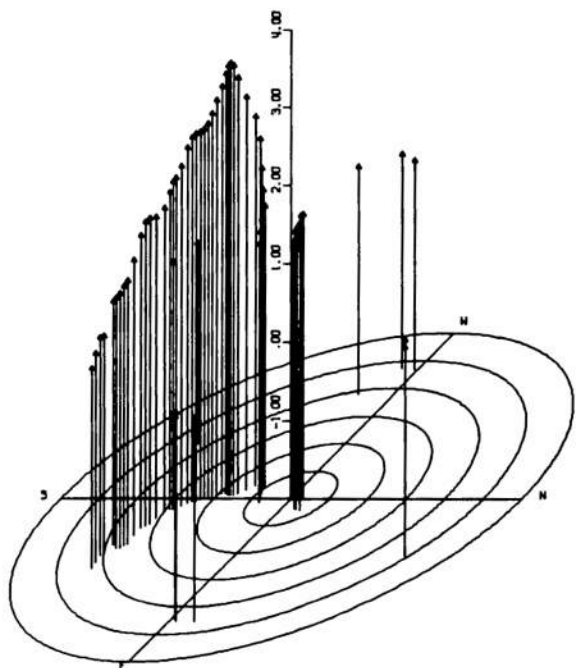
1001-1030 09SEP65 52 M0110 W529 T31SF1A122-151 RUN14



1101-1130 09SEP65 52 M0110 W534 T31SF1A182-211 RUN15



1201-1230 09SEP65 52 M0123 W530 T31SF1A262-271 RUN16



1301-1330 09SEP65 52 M0120 W535 T31SF1A302-331 RUN17

## APPENDIX B

### A FORTRAN II PROGRAM FOR SINGLE-WAVE TRAIN ANALYSIS

The FORTRAN II listing of an IBM 704 program for the least square single-wave train analysis of a spectral matrix obtained from an array of ocean wave bottom pressure transducers is included. The listing is from the FORTRAN to ALGOL translator of the Burroughs B-5500 and is syntax free at the FORTRAN II level. The mathematics of the single-wave train analysis is described in the body of this report. The data collection system and calculation of the required cross spectral matrix is described in Bennett et al (June 1964). The plotter subroutines GPHPVW and PFB3D are also included. Bennett (March 1968) describes the plotting technique in PFB3D which was used to produce the plots in Appendix A.

FORTTRAN TO ALGOL TRANSLATOR  
PHASE 1 FORTTRAN STATEMENTS

C LISTING OF AN IBM 704 FORTTRAN PROGRAM FOR DIRECTIONAL WAVE ANALYSIS.

C 13350-2 C BENNETT JULY 1967 SWOC 78-301-8210

C REQUEST-0268

C LEAST SQUARE SINGLE WAVE TRAIN FIT AFTER MUNK

DIMENSION ID(11),FQ(100),WN(100),PERIOD(100),WAVLGH(100),THMAX(100  
X),DEPATN(100),AVEP(100),P(100,6,6),EMAX(100),TEM(146)

DIMENSION D(6,6),PSI(6,6),E(100,72),THETA(72),DE(73),THZRU(146),  
XH(100),H1(100),H2(100),GOOD(6)

DIMENSION DATA (1000)

E2TEN=0.43429448

TWOPI=6.281853

RTD=57.29578

DTR=0.0174532925

FIV=0.087266465

REWIND 3

REWIND 9

CALL PLOTS(DATA(1000),1000)

CALL PLOT(0.0,-30.0,-3)

CALL PLOT(2.5,2.5,-3)

DO 5 I=1,72

ZI=(I-1)\*5

5 THETA(I)=ZI\*DTR

```

      DO 10 I=1,6
      DO 10 J=1,6
      D(I,J)=0.0
10 PSI(I,J)=0.0
      D(1,2)=100.0
      D(1,3)=100.0
      D(1,4)=100.0
      D(1,5)=100.0
      D(1,6)=100.0
      D(2,3)=117.558
      D(2,4)=190.212
      D(2,5)=190.212
      D(2,6)=117.558
      D(3,4)=117.558
      D(3,5)=190.212
      D(3,6)=190.212
      D(4,5)=117.558
      D(4,6)=190.212
      D(5,6)=117.558
C      PSI IS TRIG ANGLE
C      D IS DISTANCE
      PSI(1,2)=0.0
      PSI(1,3)=72.0*DTR
      PSI(1,4)=144.0*DTR

```

PSI(1,5)=216.0\*DTR

PSI(1,6)=288.0\*DTR

PSI(2,3)=126.0\*DTR

PSI(2,4)=162.0\*DTR

PSI(2,5)=198.0\*DTR

PSI(2,6)=234.0\*DTR

PSI(3,4)=198.0\*DTR

PSI(3,5)=234.0\*DTR

PSI(3,6)=270.0\*DTR

PSI(4,5)=270.0\*DTR

PSI(4,6)=306.0\*DTR

PSI(5,6)=342.0\*DTR

C GOOD(I)= 1 FOR USABLE CHANNEL DATA AND 0 FOR BAD CHANNEL

15 READ 2, ISKIP , (GOOD(I), I=1,6)

2 FORMAT(I2 ,6F1.0 )

IF(ISKIP)100,30,20

20 DO 25 I=1,ISKIP

READ TAPE 3, ID, FQ(1), WN(1), M, K

IF(K)21,22,21

21 PAUSE 20202

C TAPE OUT OF PHASE WITH DATA READ DESIRED

GO TO 15

22 MP=M+1

DO 23 L=2,MP



```

23 READ TAPE 3
25 CONTINUE

    GO TO 15

C    FQ(1)=0.0 CAN NOT BE MEANINGFULLY PROCESSED

30 READ TAPE 3,10,FQ(1),WN(1),M,K

    IF(K)21,31,21

31 MP=M+1

    DO 32 L=2,MP

32 READ TAPE 3,10,FQ(L),WN(L),M,K,DELTAT,DEPTH,PERIOD(L),WAVLGH(L),
    XDEPATN(L),AVER(L),((P(L,I,J),J=1,6),I=1,6)

C    P(L,I,J)=-0.0 IF CHANNEL I OR J IS NO GOOD

C    WN(L) IS WAVE NUMBER=2PI/WAVE LENGTH IN FEET

C    PI=3.1415927...

C    VALUE K NO LONGER NEEDED

    GOODCH=0.0

    DO 40 I=1,6

        GOOD(I)=GOOD(I)*P(2,I,1)

        IF(GOOD(I))41,40,41

41 GOODCH=GOODCH+1.0

    GOOD(I)=1.0

40 CONTINUE

    TERMS=1.0+(GOODCH*(GOODCH-1.0))

    DO 70 L=2,MP

    SUM=0.0

```

```

      DO 50 I=1,6
      IF(GOUD(I))51,50,51
51  SUM=SUM+P(L,I,1)
50  CONTINUE
      AVEP(L)=SUM/GOODCH
      DO 60 K=1,72
      SUM=0.0
      DO 90 I= 1,5
      IF(GOUD(I) )90,90,91
91  IP = I+1
      DO 95 J= IP,6
      IF(GOUD(J) )95,95,92
92  SUM = SUM+P(L,I,J)*COSF(WN(L)*D(I,J)*COSF(THETA(K)-PSI(I,J)))
      X      -P(L,J,I)*SINF(WN(L)*D(I,J)*COSF(THETA(K)-PSI(I,J)))
95  CONTINUE
90  CONTINUE
60  E(L,K)=(AVEP(L)+2.0*SUM)/TERMS
      IF(SENSE SWITCH 1)62,63
62  PRINT6,FQ(L),AVEP(L),(ID(I),I=1,11),(E(L,K),K=1,72)
      6  FORMAT(1X,1PE11.4,1PE12.4,11A6/(10(1X,1PE11.4)))
63  G=0.1/DTR
C    DELTA THETA=50DEG OR H=1/2*DEL THETA
      DE(1)=G*(E(L,2)-E(L,72))
      DE(72)=G*(E(L,1)-E(L,71))

```

```

DO 61 ITHETA=2,71
61 DE(ITHETA)=G*(E(L,ITHETA+1)-E(L,ITHETA-1))
DE(73)=DE(1)
K=1
DO 65 I=1,72
IF(DE(I)*DE(I+1))66,67,65
66 ZI=I-1
C FIV IS 5 DEG IN RADIANS
THZRO(K)=FIV*(ZI+(DE(I)/(DE(I)-DE(I+1))))
K=K+1
GO TO 65
67 IF(DE(I))68,69,68
69 THZRO(K)=FIV*FLOATF(I-1)
K=K+1
68 IF(DE(I+1))65,64,65
64 THZRO(K)=FIV*FLOATF(I)
K=K+1
65 CONTINUE
NZEROS=K-1
DO 75 K=1,NZEROS
C TERMS SAME AS ABOVE
SUM=0.0
DO 76 I=1,5
IF(GOOD(I))76,76,77

```

```

77 IP=I+1
   DO 79 J=IP,6
      IF(GOUD(J))79,79,78
78 SUM = SUM+P(L,I,J)*COSF(WN(L)*D(I,J)*COSF(THZRO(K)-PSI(I,J)))
   X      -P(L,J,I)*SINF(WN(L)*D(I,J)*COSF(THZRO(K)-PSI(I,J)))
79 CONTINUE
76 CONTINUE
75 TEM(K)=(AVEP(L)+2.0*SUM)/TERMS
   EMAX(L)=TEM(1)
   THMAX(L)=RTD*(TWOPI-THZRO(1))
   DO 74 K=2,NZERS
      IF(EMAX(L)-TEM(K))73,74,74
73 EMAX(L)=TEM(K)
   THMAX(L)=RTD*(TWOPI-THZRO(K))
C   THMAX IS BEARING FROM MAGNITIC NORTH
74 CONTINUE
   SUM=0.0
   DO 80 I=1,5
      IF(GOUD(I))80,80,81
81 IP=I+1
   DO 83 J=IP,6
      IF(GOUD(J))83,83,82
82 SUM=SUM+P(L,I,J)*P(L,I,J)+P(L,J,I)*P(L,J,I)
83 CONTINUE

```

80 CONTINUE

SSQ=AVEP(L)\*AVEP(L)+2.0\*SUM

H(L)=SSQ-TERMS\*EMAX(L)\*EMAX(L)

ATILDA=AVEP(L)/TWUPI

HTILDA=SSQ-ATILDA\*ATILDA\*TERMS

H1(L)=1.0-(H(L)/HTILDA)

H2(L)=(EMAX(L)-ATILDA)/(AVEP(L)-ATILDA)

IF(SENSE SWITCH 1)99,70

99 PRINT7, TERMS,EMAX(L),ATILDA,HTILDA

7 FORMAT(1X,F5.1,1P3E11.4 )

70 CONTINUE

PRINT 3,(ID(I),I=1,11) ,(GOOD(I),I=1,6),M

3 FORMAT(1H1,39HLEAST SQUARE SINGLE WAVE TRAIN FIT OF ,11A6/

X1X,6F2.0,2X,2HM=I3//

X3X,9HFREQUENCY,5X,5HPERIOD,3X,11H WAVE LENGTH,1X,11HATTENUATION,4X,

X5HAVE P,8X,1HA,10X,5HBRNG ,8X,1HH,12X,2HH1,10X,2HH2)

PRINT 4,(FQ(L),PERIOD(L),WAVLGH(L),DEPATN(L),AVEP(L),EMAX(L),

XTHMAX(L),H(L),H1(L),H2(L),L=2,MP)

4 FORMAT(1X,0PF11.7,3X,0PF9.5,1X,0PF11.4,1X,1PE11.4,

X 1X,1PE11.4,1X,1PE11.4,3X,0PF7.2,3X,1PE11.4,4X,0PF6.3,6X,0PF6.3 )

DO 110 L=2,MP

AVEP(L)=E2TEN\*LOGF(ABSF(AVEP(L)))

EMAX(L)=E2TEN\*LOGF(ABSF(EMAX(L)))

110 WAVLGH(L)=EMAX(L)-E2TEN\*LOGF(ABSF(DEPATN(L)))

```

AVEP(1)=AVEP(2)
EMAX(1)=EMAX(2)
WAVLGH(1)=WAVLGH(2)
CALL SYMBOL(2.0,0.75,0.1,14,HWAVE TRAIN.FN=      ,0.0,14)
CALL NUMBER(3.5,0.75,0.1,FQ(MP),0.0,2)
CALL GPHPVW(MP,ID,AVEP,EMAX,WAVLGH)
C   WAVLGH IS SURFACE WAVE STAFF SPECTRUM EST FROM BOTTOM PRESSURE.
C   AVE=P   EMAX=V   WAVLGH=W   ON THE PLOTS.

ZM=M
NP=DELTAT*ZM*0.5+1.0
DETX=0.0
DO 115 I=1,6
CALL NUMBER(DETX,0.1,0.1,GOOD(I),0.0,-1)
115 DETX=DETX+0.1
CALL PFB3D(NP,ID,EMAX,FQ,THMAX)
GO TO 15
100 REWIND 3
CALL EXIT
PAUSE 70707
GO TO 15
C   END(0,1,1,0,1)
END

```

FORTRAN TO ALGOL TRANSLATOR  
PHASE 1 FORTRAN STATEMENTS

```
SUBROUTINE GPHPVW(L, ID, ZLOGP, ZLOGV, ZLOGW)
C SPECIAL FORM OF GPHPVW FOR 1335D-2 AUGUST 1967
  DIMENSION ZLOGP(2), ZLOGV(2), ZLOGW(2), ID(2)
  CALL PLOT(0.0, 0.0, 3)
  CALL PLOT (0.0, 10.5, 2)
  CALL PLOT (8.0, 10.5, 2)
  CALL PLOT (8.0, 0.0, 2)
  CALL PLOT (0.0, 0.0, 2)
  CALL PLOT (2.0, 1.5, -3)
  CALL SYMBOL (0.0, -1.0, -.1, ID(1), 0.0, 66)
  CALL AXIS (0.0, 0.0, 20HNORMALIZED FREQUENCY, -20, 5.0, 0.0, 0.0, 0.2)
  ZMAX=ZLOGP(1)
  DO 10 I=2, L
    COMPAR=ZLOGP(I)
10  ZMAX=MAX1F(ZMAX, COMPAR)
  MAX=ZMAX+3.0
  BE=MAX-8
  CALL AXIS(0.0, 0.0, 17HLOG POWER DENSITY, 17, 8.0, 90.0, BE, 1.0)
  DX=5.0/FLOATF(L-1)
  Y=ZLOGP(1)-BE
  X=0.0
  CALL PLOT(X, Y, 3)
```

```

DO 20 I=2,L
X=X+DX
Y=ZLOGP(I)-BE
20 CALL PLOT (X,Y,2)
CALL SYMBOL(X,Y,0.1,1HP,0.0,1)
X=5.0
Y=ZLOGV(L)-BE
CALL SYMBOL(X,Y,0.1,1HA,0.0,1)
CALL PLOT(X,Y,3)
M=L-1
DO 21 I=1,M
X=X-DX
II=L-I
Y=ZLOGV(II)-BE
21 CALL PLOT(X,Y,2)
WMAX=MAX
X=0.0
Y=ZLOGW(1)-BE
CALL PLOT(X,Y,3)
DO 22 I=2,L
X=X+DX
IF(ZLUGW(I)-WMAX)24,23,23
23 Y=8.0
GO TO 22

```



```
24 Y=ZLOGW(I)-BE
22 CALL PLOT(X,Y,2)
    CALL SYMBOL(X,Y,0.1,1HS,0.0,1)
    IF (SENSE LIGHT 1)40,30
30 CALL PLOT (-2.0,9.0,-3)
    SENSE LIGHT 1
    GO TO 50
40 CALL PLOT (6.0,-12.0,-3)
50 RETURN
C    END(0,1,1,0,0)
    END
```

FORTRAN TO ALGOL TRANSLATOR  
PHASE 1 FORTRAN STATEMENTS

```
SUBROUTINE PF93D(N, ID, P, R, B)

C   P=FUNCTION OF R = POWER DENSITY
C   B= FUNCTION OF R = COMPASS BEARING
C   R= FREQUENCY IN HZ

DIMENSION ID(2), P(2), R(2), B(2), C(360), S(360)

T=10.0
D=0.70710678
OTH=0.017453293
C   DTH IS ONE DEGREEE IN RADIAN'S IE RADIAN'S PER 1 DEGREE
A=0.0
DO 10 I=1,360
  A=A+OTH
  C(I)=COSF(A)
10 S(I)=SINF(A)

  CALL PLOT(0.0,0.0,3)
  CALL PLOT(0.0,10.5,2)
  CALL PLOT(8.0,10.5,2)
  CALL PLOT(8.0,0.0,2)
  CALL PLOT(0.0,0.0,2)
  CALL SYMBOL(1.0,0.5,-0.1, ID(1),0.0,66)
  CALL PLOT(4,0,3.5,-3)
  CALL PLOT(3.0,0.0,2)
```

```

CALL SYMBOL(3.25,0.0,0.1,1HN ,0.0,1)
CALL AXIS(0.0,1.0,0H ,0,5.0,90.0,-1.0,1.0)

CALL PLOT(0.0,1.0,3)
CALL PLOT(0.0,0.0,2)
CALL PLOT(-3.0,0.0,2)
CALL SYMBOL(-3.26,0.0,0.1,1HS ,0.0,1)
X=-3.0*D
Y=X
CALL SYMBOL(X-0.1,Y-0.1,0.1,1HE ,0.0,1)
CALL PLOT(X,Y,3)
CALL PLOT(-X,-Y,2)
CALL SYMBOL(0.1-X,0.1-Y,0.1,1HW ,0.0,1)
CALL PLOT(0.0,0.0,-3)
DO 20 I=1,6
A=0.5*FLOAT(I)
CALL PLOT(A,0.0,3)
DO 30 J=1,360
Y=A*S(J)*D
X=A*C(J) + Y
30 CALL PLOT(X,Y,2)
20 CONTINUE
CALL PLOT(0.0,0.0,-3)
D=10.0*D
C 10*D NEEDED TO SCALE 0.0-0.3 TO 0-3 INCHES ON PLOTS

```

```

DO 40 I=2,N
RAD=DTH*B(I)
Y=R(I)*D*SINF(-RAD)
X=R(I)*T*COSF(RAD) + Y
IUD=3
CALL PLOT(X,Y,IUD)
AY=P(I) + Y + 1.96
C 2 IS NOT ADDED SO TOP SYMBOL WILL BE THE REFERENCE IN .08 SYMBOL
CALL PLOT(X,AY,2)
CALL SYMBOL(X,AY,0.08,2,0.0,-2)
CALL PLOT(X,AY,3)
40 CALL PLOT(X,Y,2)
IF(SENSE LIGHT 1)41,42
42 CALL PLOT(-4.0,7.0,-3)
SENSE LIGHT 1
GO TO 50
41 CALL PLOT(4.0,-14.0,-3)
50 RETURN
C END(0,1,1,0,1)
END

```

## APPENDIX C

### A FORTRAN PROGRAM FOR ITERATIVE WAVE TRAIN ANALYSIS

The FORTRAN listing of a Burroughs B-5500 program for the iterative least square multiple wave train analysis of a spectral matrix is presented. The mathematics is an iterative utilization of the single wave train analysis described in the body of this report. Following the single wave train analysis of the measured spectral matrix the resulting values of single wave train power,  $A$ , and wave bearing,  $\theta$ , are used to find the spectral matrix that would occur for such a wave. Details for this are given in Section 5 of this report. From the above, a residual measured spectral matrix is formed by subtracting a fractional portion of the single wave spectral matrix from the previously used spectral matrix. The residual spectral matrix is then single wave train analyzed. The above procedure is continued iteratively until a specified number of iterations have been completed or the residual spectral matrix total power gets smaller than a specified value. Table C1 shows numerical results for several frequencies. Figure C1 is a plot of the bearing,  $\theta$ , and the ratio of  $A$  to the total power available in the original measure spectral matrix for the frequency band 0.00833 to 0.24187 Hz. The iteration parameters were set for a maximum of five iterations, a residual power ratio of 0.1, and a fractional portion value of 0.1. Both results are for data collected for task SWOC at Stage II between 1220 and 1249 hours on 4 June 1965. The wind speed was 12 knots from a bearing of 280 degrees. In Table C1  $A$ ,  $H$ , and bearing are as previously defined. AVE P is the average  $C_{11}(f)$  for the residual spectral matrix and  $P$  is the AVE P for the first iteration; i.e., the original measured average power. The  $H1$  and  $H2$  values are measures of the isotropicity of the energy represented by the residual spectral matrix.  $H1$  compares the least square value of  $H$  with the value  $H'$  that would have been obtained if the wave energy were isotropic:

$$H1 = 1 - (H/H') .$$

$H2$  compares the power  $A$  of a single wave fit to the total power, AVE  $P$ , and the value  $A'$  that would have been obtained for isotropic energy:

$$H2 = (A-A')/(AVE P-A') .$$

Both  $H1$  and  $H2$  are between 0 and 1, the lower limit is for the isotropic case and the upper for a plane wave from a single direction.

TABLE C1

## SOME NUMERICAL RESULTS OF ITERATIVE DIRECTIONAL ANALYSIS

FREQUENCY		ITERATION		AVE P		BEARING		A/P		H		H1		H2	
0.058333															
C-2	FREQUENCY	ITERATION	A	AVE P	BEARING	A/P	H	H1	H2						
			2.7023E-01	4.5520E-01	4.59	0.594	7.0425E-01	0.749	0.517						
			2.4821E-01	4.2817E-01	4.59	0.534	7.0425E-01	0.706	0.486						
			2.1849E-01	4.0385E-01	4.59	0.481	7.0425E-01	0.658	0.455						
			1.9710E-01	3.8196E-01	4.59	0.433	7.0425E-01	0.607	0.424						
FREQUENCY	ITERATION		A	AVE P	BEARING	A/P	H	H1	H2						
			1.7720E-01	3.6226E-01	54.19	0.394	6.8325E-01	0.566	0.399						
			2.3621E-01	4.6936E-01	11.05	0.503	7.8311E-01	0.665	0.409						
			2.1259E-01	4.4572E-01	11.05	0.453	7.8311E-01	0.614	0.378						
			1.9133E-01	4.2446E-01	11.05	0.408	7.8311E-01	0.559	0.347						
FREQUENCY	ITERATION		A	AVE P	BEARING	A/P	H	H1	H2						
			1.7219E-01	4.0533E-01	11.04	0.367	7.8311E-01	0.502	0.316						
			1.5715E-01	3.8811E-01	56.13	0.335	7.6205E-01	0.459	0.292						
			1.5856E-01	4.6426E-01	5.29	0.342	7.7033E-01	0.442	0.217						
			1.4270E-01	4.4840E-01	5.29	0.307	7.7033E-01	0.331	0.189						
0.083333	FREQUENCY	ITERATION	A	AVE P	BEARING	A/P	H	H1	H2						
			1.2343E-01	4.3413E-01	5.29	0.277	7.7033E-01	0.320	0.163						
			1.1359E-01	4.2129E-01	10.43	0.249	7.7032E-01	0.263	0.137						
			1.0755E-01	4.0973E-01	194.55	0.236	7.3312E-01	0.247	0.129						
			2.0211E-01	5.5432E-01	193.72	0.365	7.2767E-01	0.585	0.244						
FREQUENCY	ITERATION		A	AVE P	BEARING	A/P	H	H1	H2						
			1.8190E-01	5.3411E-01	193.72	0.328	7.2767E-01	0.524	0.216						
			1.6371E-01	5.1522E-01	193.72	0.295	7.2767E-01	0.461	0.189						
			1.4734E-01	4.9255E-01	193.72	0.266	7.2767E-01	0.396	0.161						
			1.3250E-01	4.8441E-01	193.72	0.239	7.2767E-01	0.331	0.136						
0.091667	FREQUENCY	ITERATION	A	AVE P	BEARING	A/P	H	H1	H2						
			4.7256E-01	9.1547E-01	192.42	0.524	9.7927E-01	0.869	0.434						
			4.3170E-01	8.6750E-01	192.42	0.472	9.7927E-01	0.841	0.403						
			3.8953E-01	8.2433E-01	192.42	0.424	9.7927E-01	0.809	0.371						
			3.4757E-01	7.8548E-01	192.42	0.382	9.7927E-01	0.771	0.340						
FREQUENCY	ITERATION		A	AVE P	BEARING	A/P	H	H1	H2						
			3.1471E-01	7.5051E-01	192.42	0.344	9.7927E-01	0.729	0.309						
0.100000	FREQUENCY	ITERATION	A	AVE P	BEARING	A/P	H	H1	H2						
			1.2352E-00	1.8884E-00	192.65	0.654	3.1192E-00	0.934	0.589						
			1.1117E-00	1.7649E-00	192.65	0.589	3.1192E-00	0.920	0.560						
			1.0005E-00	1.6537E-00	192.65	0.530	3.1192E-00	0.903	0.530						
			9.0047E-01	1.5537E-00	192.65	0.477	3.1192E-00	0.882	0.500						
FREQUENCY	ITERATION		A	AVE P	BEARING	A/P	H	H1	H2						
			8.1042E-01	1.4636E-00	192.65	0.429	3.1192E-00	0.857	0.469						

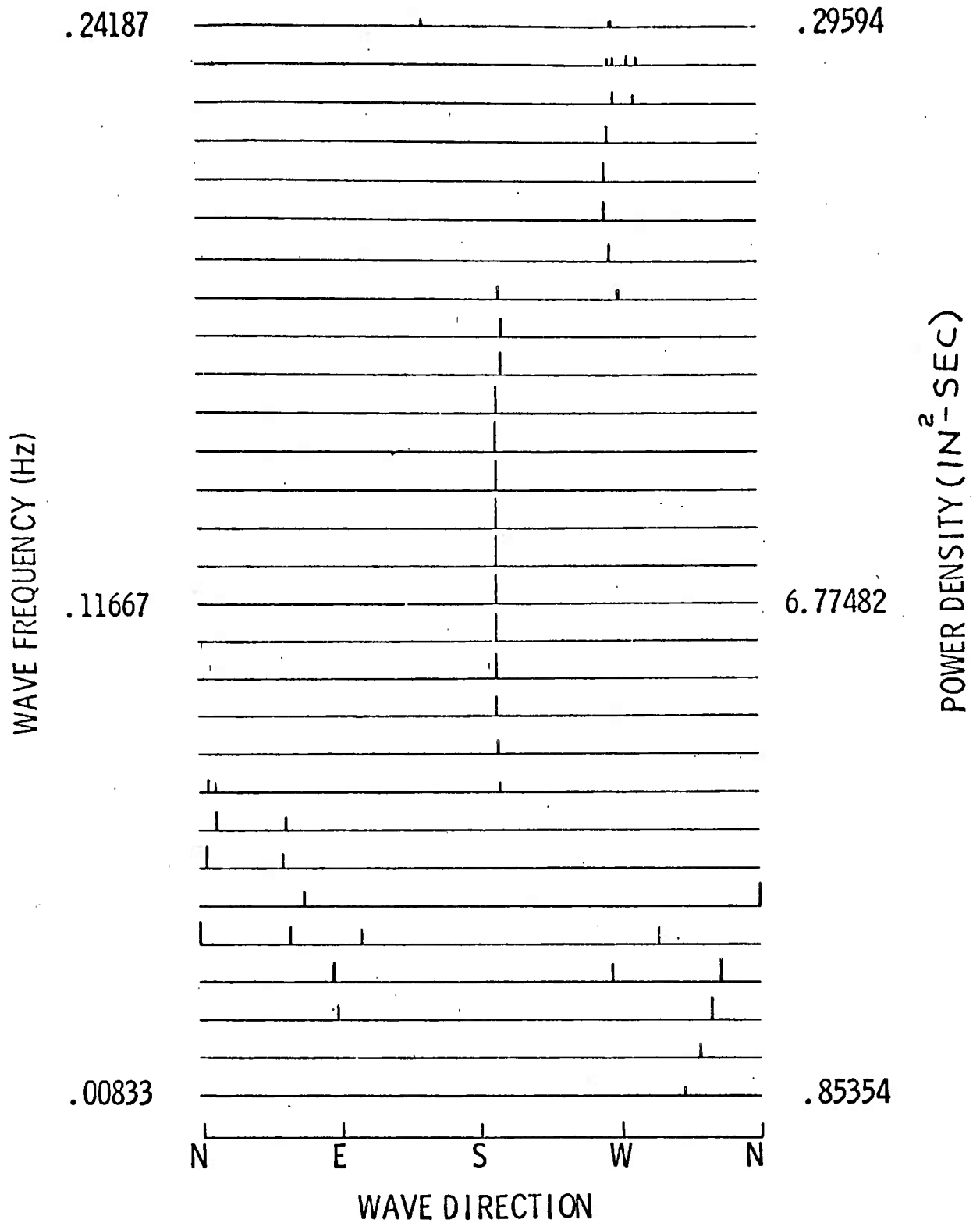


FIGURE C1. ITERATIVE LEAST SQUARE WAVE FIT DIRECTIONAL ANALYSIS





TABLE C2 (CONTINUED)

```

PSI(1,3)=72.0*DTX
PSI(1,4)=144.0*DTX
PSI(1,5)=216.0*DTX
PSI(1,6)=288.0*DTX
PSI(2,3)=126.0*DTX
PSI(2,4)=162.0*DTX
PSI(2,5)=198.0*DTX
PSI(2,6)=234.0*DTX
PSI(3,4)=198.0*DTX
PSI(3,5)=234.0*DTX
PSI(3,6)=270.0*DTX
PSI(4,5)=270.0*DTX
PSI(4,6)=306.0*DTX
PSI(5,6)=342.0*DTX
GOO(1)=1 FOR USABLE CHANNEL DATA AND 0 FOR BAD CHANNEL
READ(6,2) (GUO(I),I=1,6),LF,MF,MAXITR,RATIO,PERCENT,DXFQ
2 FORMAT(6F1.0,3I6,5F6.0)
CLOSE 6
IF (DXFQ.LT. 0.2 ) DXFQ = 0.2
DXP=2.0*DXFQ
READ (3) IO,FQ(1),WN(1),M,K
MP=M+1
DO 32 L=2,MP
32 READ (3) IO,FQ(L),WN(L),M,K,DELTAT,DEPTH,PERIOD(L),WAVLGH(L),
1 DEPATN(L),AVP(L),((P(L,I,J),J=1,6),I=1,6)
CLOSE 3
P(L,I,J)=0.0 IF CHANNEL I OR J IS NO GOOD
WN(L) IS WAVE NUMBER=2PI/WAVE LENGTH IN FEET
PI=3.1415927...
VALUE K NO LONGER NEEDED
GOUNCH=0.0
DO 40 I=1,6
GOO(I)=GUO(I)*P(2,I,1)
IF(GUO(I))41,40,41
41 GOUNCH=GOUNCH+1.0
GOO(I)=1.0
40 CONTINUE
TERMS=1.0+(GOUNCH*(GOUNCH-1.0))
AXIS AND LABEL FOR BEARING VS FREQUENCY PLOT OF (EMAX,THMAX),
DELY=-0.2
DO 42 I=1,6
CALL NUMBER(0.1,DELY,0.07,GOO(I),-90.0,-1)
DELY=DELY+0.1
42 CALL SYMUL(0.5,-1.25,0.14,IO(I),-90.0,60)
CALL SYMROL(0.5,-9.63,0.14,IO(11),-90.0,6)
RCO(1)='WAVE D'

```

```

00034400
00034500
00034600
00034700
00034800
00034900
00035000
00035100
00035200
00035300
00035400
00035500
00035600
00035700
00035800
00035900
00036000
00036100
00036200
00036300
00036400
00036500
00036600
00036700
00036800
00036900
00037000
00037100
00037200
00037300
00037400
00037500
00037600
00037700
00037800
00037900
00038000
00038100
00038200
00038300
00038400
00038500
00038600
00038700
00038800
00038900
00039000

```

TABLE C2 (CONTINUED)

```

      HCD(2)="THRECI"
      HCD(3)="IN"
      CALL SYNRUL(1.0,-4.0,0.14,HCD(1),-90.0,14)
      CALL PLUT(1.5,-1.75,-3)
      CALL PLUT(-0.1,0.0,2)
      CALL PLUT(0.0,0.0,2)
      CALL PLUT(0.0,-1.8,2)
      CALL PLUT(-0.1,-1.8,2)
      CALL PLUT(0.0,-1.8,2)
      CALL PLUT(0.0,-3.6,2)
      CALL PLUT(-0.1,-3.6,2)
      CALL PLUT(0.0,-3.6,2)
      CALL PLUT(0.0,-5.4,2)
      CALL PLUT(-0.1,-5.4,2)
      CALL PLUT(0.0,-5.4,2)
      CALL PLUT(0.0,-7.2,2)
      CALL PLUT(-0.1,-7.2,2)
      HCD(1)="V"
      CALL SYNRUL(-0.25,-7.1,0.14,HCD(1),-90.0,1)
      HCD(1)="W"
      CALL SYNRUL(-0.25,-5.1,0.14,HCD(1),-90.0,1)
      HCD(1)="S"
      CALL SYNRUL(-0.25,-3.5,0.14,HCD(1),-90.0,1)
      HCD(1)="E"
      CALL SYNRUL(-0.25,-1.7,0.14,HCD(1),-90.0,1)
      HCD(1)="V"
      CALL SYNRUL(-0.25,0.1,0.14,HCD(1),-90.0,1)
      HCD(1)="WAVE F"
      HCD(2)="REQJEN"
      HCD(3)="CYC12"
      CALL SYNRUL(5.0,1.0,0.14,HCD(1),0.0,18)
      HCD(1)="POWER";HCD(2)="DENSITY";HCD(3)="V"
      CALL SYNRUL(5.0,-9.75,0.14,HCD(1),0.0,13)
      PRINT A,C(1),I=1,11),(G00D(I),I=1,6)*MAXITR,RATIO,F3(LF),FQ(MF)
      1, PERCENT
      A FORMAT(11F10.4,11X,MULTIPLE WAVE TRAIN FIT OF ",11A6/0012600
      1 1X,6F2.0," MAXIMUM ITERATION=",I4," MINIMUM RATIO=",F7.3,1X,
      2 FREQUENCY RANGE (",2F9.6,"), " PERCENT=",F7.3)
      DO 70 L=LF,MF
      ITR=0
      PRINT 9, FQ(L)
      9 FORMAT(11F10.4,11X,MULTIPLE WAVE TRAIN FIT OF ",11A6/0012600
      1 " A/P
      11 H2"/(1X,F9.6))
      700 SUM=0.0; ITR= ITR +1; IF( ITR .GT. MAXITR) GO TO 70
      DO 50 I=1,6
      IF(G00D(I))51,50,51
      51 SUM=SUM+D(L,I,1)
      00091100
      0009200
      0009300
      0009400
      0009500
      0009600
      0009700
      0009800
      0009900
      0010000
      0010100
      0010200
      0010300
      0010400
      0010500
      0010600
      0010700
      0010800
      0010900
      0011000
      0011100
      0011200
      0011300
      0011400
      0011500
      0011600
      0011700
      0011800
      0011900
      0012000
      0012100
      0012200
      0012300
      0012400
      0012500
      0012600
      0012700
      0012800
      0012900
      0013000
      0013100
      0013200
      0013300
      0013400
      0013500
      0013600
      0013700

```

TABLE C2 (CONTINUED)

```

50 CONTINUE
  AVEP=SUM/GDDNCH
  IFC AVEP .LE. 0) GO TO 70
  IFC ITR .NE. 1) GO TO 600
  PMAX=AVEP
  CALL PLN(DXFA,0.0,-3)
  CALL NUMBER(0.0,0.8,0.07,FQ(L),-90.0, 5)
  CALL PLN(0.0,0.3) ; CALL PLN(0.0,-7.2,2)
  CALL NUMBER(0.0,-7.5,0.07,PMAX,-90.0, 5)
600 CONTINUE
  DO 60 K=1,72
  SUM=0.0
  DO 90 I= 1,5
  IF(GDDN(I)) 90,90,91
91 IP = I+1
  DO 95 J= IP,6
  IF(GDDN(J)) 95,95,92
92 SUM = SUM+P(L,I,J)*COS(WN(L)*D(I,J)*COS(THETA(K))-PSI(I,J)))
  -P(L,J,I)*SIN(WN(L)*D(I,J)*COS(THETA(K))-PSI(I,J)))
  X
95 CONTINUE
90 CONTINUE
60 EK)=(AVEP + 2.0*SUM)/TERMS
62 G=0.1/DIR
  DELTA THETA=5DEG OR H=1/2*DEL THETA
  DE(1)=G*(EC 2)-E( 72)
  DE(72)=G*(EC 1)-E( 71)
  DO 61 ITHETA=2,71
  DE(ITHETA)=G*(EC ITHETA+1)-E( ITHETA-1)
  DE(73)=DE(1)
  K=1
  DO 65 I=1,72
  IF(DE(I)*DE(I+1)) 66,67,65
66 ZI=I-1
  FIV IS 5 DEG IN RADIAN
  THZRDK(K)=FIV*(ZI+(DE(I)/(DE(I)-DE(I+1))))
  K=K+1
  GO TO 65
67 IF(DE(I)) 68,69,69
69 THZRDK(K)=FIV*FLNAT(I-1)
  K=K+1
68 IF(DE(I+1)) 65,64,65
64 THZRDK(K)=FIV*FLNAT(I)
  K=K+1
65 CONTINUE
  NZEROS=K-1
  DO 75 K=1,NZEROS
  TERMS SAME AS ABOVE
  C

```

TABLE C2 (CONTINUED)

```

SUM=0.0
00 76 I=1.5
IF(GN00(I)) 76,76,77
77 IP=I+1
00 79 J=IP,6
IF(GN00(J)) 79,79,7A
7A SUM = SUM+P(L,I,J)*CNS(WN(L)*D(I,J)*CNS(TH/R0(K)-PSI(I,J)))
X
-P(L,J,I)*STN(WN(I)*D(I,J)*CNS(TH/R0(K)-PSI(I,J)))
79 CONTINUE
76 CONTINUE
75 TEM(K)=(AVEP + 2.0*S14)/TERMS
EMAX = TEM(1)
RDMAX = THZR0(1)
TRIG TO COMPASS CONVERSION OF THETA
THMAX = RTD*(TW0PI-THZR0(1))
00 74 K=2,NTERMS
IF(EMAX-TEM(K)) 73,74,74
73 EMAX = TEM(K)
RDMAX = THZR(K)
THMAX = RTD*(TW0PI-THZR(K))
THMAX IS BEARING FROM MAGNETIC NORTH
74 CONTINUE
TEST = EMAX/PMAX
SUM=0.0
00 80 I=1.5
IF(GN00(I)) 80,80,81
81 IP=I+1
00 83 J=IP,6
IF(GN00(J)) 83,83,82
82 SUM=SUM+P(L,I,J)*D(L,I,J)+P(L,J,I)*P(L,J,I)
83 CONTINUE
80 CONTINUE
SSQ = AVEP * AVEP + 2.0*SUM
H = SSQ -TERMS* FMAX*EMAX
ATILDA = AVEP/TW0PI
ATILDA=SSQ-ATILDA*ATILDA*IFRMS
H1 = 1.0 -(H /HTILDA)
H2 = (EMAX-ATILDA)/(AVEP-ATILDA)
Y = -7.2 * (THMAX/360.0): X = TEST * DXFQ
CALL PLOT(X,Y,2)
ITERATION A AVE P BEARING RATIO H H1 H2
PRINT 7, ITR, EMAX, AVEP, THMAX, TEST, H, H1, H2
7 FORMATT 14X, I4,5X,1PE11,4,1PE13,4,0PF0,2,F8,3,1PE12,4,0PF1,3)
IF(TEST .LT. RATIO) G.1 TO 70
00 710 I=1.6
IF(GN00(I)) 710,710,710
710 CONTINUE

```

# TABLE C2 (CONTINUED)

```

00 730 I= 1,5 IF(GOOD(I) .EQ. 0) GO TO 730
IP = I+1
00 720 J= IP,6 IF(GOOD(J) .EQ. 0) GO TO 720
P(L,I,J) = P(L,I,J) - (PERCENT *(EMAX* COS(WN(L)*D(I,J))*
1 COS(RDMAX - PSI(I,J)))) 00023500
1 P(L,J,I) = P(L,J,I) + (PERCENT *(EMAX* SIN(WN(L)*D(I,J))*
1 COS(RDMAX - PSI(I,J)))) 00023600
                                00023700
                                00023800
                                SEGMENT
                                START OF SEGMENT
720 CONTINUE 00023900
730 CONTINUE 00024000
GO TO 700 00024100
70 CONTINUE 00024200
100 CALL PLOT(0,0,999) 00024300
                                00024400
                                00024500
                                00024600
                                00024700
                                00024800
                                SEGMENT
                                00024900

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